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Methodology Investigation
Phase I Report

Nuclear Radiation Metrology Methods

May 1992

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The objective of this investigation was to assess the ability of USAEPG to perform required RADIAC testing using currently recognized standards of performance and quality assurance, and to recommend actions which will lead to improved methodology, i.e., capabilities, test procedures, and quality assurance. To this end, the authors of this Phase I report have reviewed USAEPG RADIAC facilities, procedures, personnel training, staffing, library resources, and other resources. They present their findings, which include recommendations for improved procedures, quality control, documentation, professional contacts, library and other resources, training, peer review, and instrumentation. They found locally available library resources to be wholly inadequate to support current and future missions, and comment also on the professional isolation of the RADIAC staff. Appendices include: (a) an extensive list of books, reports, and periodicals deemed necessary to support USAEPG RADIAC missions; (b) "Criteria for Operation of Federally-Owned Calibration Laboratories (Ionizing Radiation)"; and (c) an extensive presentation on RADIAC calibration technology.

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DEPARTMENT OF THE ARMY
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REPLY TO ATTENTION OF

AMSTE-TC-D (70-10p)

01 APR 1992

MEMORANDUM FOR Commander, U.S. Army Electronic Proving Ground, ATTN: STEEP-MT-E, Fort Huachuca, AZ 85613-7110

SUBJECT: Methodology Investigation, Phase I Report, Nuclear Radiation Metrology Method, TECOM Project No. 7-CO-R89-EP0-005

1. Subject report is approved.

2. Point of contact at this headquarters is Mr. James Piro, AMSTE-TC-D, amstetcd@apg-9.apg.army.mil, DSN 298-2170.

FOR THE COMMANDER:

Kenneth Ballard
for FREDERICK D. MABANTA
Chief, Tech Dev Div
Directorate for Technology

FOREWORD

This report covers the Phase I of a two-phase Methodology Improvement Program to identify features of the US Army Electronic Proving Ground's (USAEPG) RADIAC equipment and procedures which need improvement. A goal of Phase I is to identify actions required in order to bring USAEPG nuclear metrology into line with current state-of-the-art, i.e., nationally recognized standards of performance and quality assurance. Phase II efforts, which will be more laboratory oriented, will respond to conclusions and recommendations developed in Phase I.

The body of this report (Section 2 and Appendices A, B, and C) is reproduced without alteration (except pagination) from the report provided by the (National Institute of Standards and Technology (NIST) investigators, Mr. Henry T. Heaton, II, Dr. Kenneth G.W. Inn, Mr. William L. McLaughlin, and Dr. Bert M. Coursey. Mr. Heaton visited USAEPG twice and Dr. Inn and Dr. McLaughlin each visited once. Mr. Heaton also visited the Primary Nucleonics Laboratory at Sacramento Army Depot, and held some discussions with technical personnel at other Army nucleonics facilities.

Some of the personnel and organizations mentioned in the NIST report have changed since its preparation. The observations, conclusions, and recommendations are unchanged.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

SECTION 3. APPENDICES

SECTION 1. SUMMARY

1.1 BACKGROUND. Over the past four decades, there has been a continuing growth of nuclear radiation generators and sources. These include weapons, reactors, and new radionuclides. Nuclear capability and expertise in reactor and weapon technology have now spread throughout the world. Timely hazard assessment due to the use or misuse of nuclear devices can only be made by means of modern radiological instrumentation termed RADIAC (Radiation Detection, Identification, and Computation) by the Army. The nuclear radiations of particular interest to the military are the electromagnetic gamma radiation and the particulate alpha, beta, and neutron emissions. Detection and measurement of nuclear radiation is dependent upon the energy, time characteristics, and quantity of radiation received at the RADIAC device. For nuclear weapon detonation, the radiation absorbed dose (rad), prompt neutron and gamma radiation up to 10,000 rads per microsecond must be measured. For radioactive fallout, contaminated items, or commodities using radioactive devices, continuous alpha, beta, and gamma radiation levels as low as 0.001 rad must be measured.

1.2 PROBLEM. This investigation is to develop test methods and identify instrumentation required to support tests of nuclear radiation measurement devices, calibration devices, and associated equipment such as charger-readers. Most military radiation instruments are designed to measure the tissue absorbed dose or dose rate received by personnel. Methods, techniques, and appropriate instrumentation to measure the energy dependence, rate dependence, neutron radiation, and mixed radiation for instruments under development are poorly defined and in some cases nonexistent. If and when RADIAC devices, such as a field tactical dosimeter, need to be employed, the user must have confidence in its proper operation. By contrast, the Army materiel

such as transportation or communications equipment are generally operated in a near to:al design environment and can subsequently be "debugged" on the basis of field reports. This cannot be done for tactical nuclear instrumentation due to treaty restrictions preventing atmospheric nuclear weapons testing. Improved test methods and simulators are needed, and could contribute tc an improved survival rate during a nuclear conflict.

1.3 OBJECTIVE. This investigation will develop test procedures and recommend instrumentation for the test of RADIAC instruments. Special emphasis will be placed upon the accuracy of tissue dose or dose rate measurement accuracy considering radiation energy and rate dependence for gamma and neutron radiation. A second priority will be to develop test procedures and recommend instrumentation to assess the measurement accuracy of alpha instruments considering radiation energy while discriminating against beta radiation. Energy dependence subtests will consider the following ranges: gamma 10 kiloelectron volts (keV) to 12 megaelectron volts (MeV), neutron 0.025 electron volts (eV) to 20 MeV, alpha 2 MeV to 7 MeV, beta 15 keV to 3 MeV. Rate dependence tests for tactical dosimeters will consider gamma, neutron, and mixed gamma neutron rates up to 10^{10} rads per second.

1.4 PROCEDURES. Personnel of the NIST visited USAEPG twice, for a total of four and a half days. During these visits, they reviewed facilities and equipment, procedures, staffing and personnel training, library resources and other resources.

1.5 RESULTS. Based upon their reviews, NIST personnel developed recommendations relative to facilities and equipment, quality assurance, documentation, professional contacts, library and other resources, peer review, and computation equipment.

1.6. ANALYSIS. No laboratory work was performed. However a result of discussions between

USAEPG and NIST personnel was a determination that characterization of the output of the cabinet x-ray unit was required, as was an assessment of gamma beam uniformity and scatter. A number of their recommendations cannot be implemented under existing organizational and financial realities. They found USAEPG library resources to be wholly inadequate to support our RADIAC missions. They emphasized that it was essential to eliminate professional isolation and increase peer contacts. Development of a quality assurance program with complete documentation of procedures and equipment used in each test was emphasized. They deemed some of our instrumentation to be obsolete and out of repair, and suggested that we should find some way to identify financial resources required to maintain state-of-the-art capabilities. They recognized that frequent turnover in enlisted military personnel not only limited the skill level at which they could be asked to perform, but occupied civilian time during repeated training of new military assignees.

1.7 CONCLUSIONS. Phase I of this investigation, reported here, was devoted to an assessment of the USAEPG RADIAC activity by NIST personnel particularly well qualified in radiation and RADIAC measurements and calibration. Unexpectedly, the NIST report focussed primarily on infrastructure, personnel, professional training, and quality assurance matters. The NIST report makes no recommendations concerning specific instrumentation upgrades required, nor does it examine or recommend specific changes in test procedures. To that extent, the objectives of this investigation were not met.

In the Phase II effort, NIST is tasked specifically to examine RADIAC TOPs and to recommend improvements, changes, and additions which will respond to most of the objectives stated in paragraph 1.3.

USAEPG does not possess the neutron or flash-gamma/x-ray sources needed to perform experiments on gamma and neutron rate dependence and neutron dosing.

1.8 RECOMMENDATIONS AND RESPONSES. Many of NIST personnel's recommendations were incorporated in paragraph 1.6, above, but are listed again here, together with others. Some of the following have been augmented by the suggestions offered during discussions between NIST and USAEPG personnel:

a. NIST recommended that RADIAC equipment and procedures at USAEPG receive peer review at least biennially, and that the peer review teams interact directly with higher management to provide updates on the quality of work, including assessment of the aspects which are being done well, and those needing improvement. Response: This recommendation was not acted upon, in large part because there are no peers at USAEPG knowledgeable in RADIAC testing.

b. NIST recommended that the Military Specifications (MIL-SPEC) and testing protocols be evaluated by technical experts for applicability and adequateness to provide the Army with the information upon which it can evaluate first article testing. Response: Evaluation of MIL-SPEC is outside our mandate. Testing protocols are being evaluated in Phase II work by NIST.

c. NIST recommended that characterization of the output energy spectrum and calibration of the kilovolts peak (kVp) of the cabinet x-ray unit be performed before energy dependence or defined energy tests. Because of the close confines of the cabinet unit, careful attention must be paid to the impact of internal scattering upon the energy spectrum to which a test item is actually exposed. At the current state of knowledge of the delivered x-ray spectrum, the cabinet unit should be limited to radiographic use and relatively non-quantitative appraisal of test item

performance and should not be employed for any tests requiring accurate knowledge of the x-rays actually delivered to the test item. Response: The cabinet x-ray unit has been removed from service pending repairs. We did perform detailed half-value layer measurements prior to its removal from service.

d. NIST recommended that Test Operating Procedures (TOPs) be completely revised and updated to reflect current technology. They also state that all TOPs should be revised to define and use up-to-date, or at least consistent, radiation quantities and units. Response: This is being performed in Phase II.

e. NIST suggested that we excess and replace currently obsolete equipment, and attempt to identify a mechanism for funding regular upgrades and replacements of equipment, to recognized standards of utility and performance. Response: Much of our obsolete equipment has been excessed. Funds have not been available to acquire modern replacements.

f. There should be more in-house instrumentation available for both x-ray and gamma-ray sources to verify the exposure rate from the radiation sources. Response: Instrumentation funds have not been available.

g. Since the present method of obtaining funding from CECOM (Communications-Electronics Command) provides little flexibility for upgrading metrology, one possible approach for obtaining additional funding would be for USAEPG to consider adding a "Development Fee" as part of the cost of doing tests for CECOM. Response: No longer applicable.

h. NIST recommended purchase of an extensive list of reference and text books, reports, and journal subscriptions needed to substitute for the absence of a library capable of supporting our mission. The list included various national and international standards. Response: Some

progress has been made in this area.

i. NIST recommended that we end our professional isolation and increase our peer contacts by attendance at workshops and meetings of the major national organizations in the field. Verbally, they also suggested visits to NIST, the Federal Emergency Management Agency (FEMA); the Armed Forces Radiobiology Research Institute (AFRRI); the Primary Nucleonics Laboratory at Sacramento Army Depot; Sandia National Laboratory, Albuquerque; and other facilities, as appropriate, where we could learn of capabilities and procedures not now in our repertoire. Response: No funds were available for travel to meetings or workshops since 1989.

j. NIST recommended, as a related matter, that professional personnel in RADIAC activities join the Health Physics Society and/or other scientific societies dealing with the subject. They also recommended participation in recognized standards bodies, such as the American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), etc. Response: D.R. Sears pursued the possibility of joining the Health Physics Society, but the required two sponsors were not available.

k. NIST recommended a more vigorous training regimen for all RADIAC personnel, civilian and military, feeling that on-the-job training fails to introduce USAEPG personnel to the procedures and practices used elsewhere, and required here. They stated that our manpower is undertrained. In discussions, they linked the need for training to the need to eliminate our professional isolation. They also suggested that the more junior personnel acquire training in college algebra, calculus, etc., to a level permitting use as everyday tools. The RADIAC staff can improve their level of expertise in the practical and theoretical aspects of radiation dosimetry by taking classes at a nearby university, attending conferences, becoming active in professional

societies, consulting with leading experts, and visiting other laboratories to discuss and compare methods and techniques. Topics which would prove useful for personnel at this facility include: nuclear physics, radiation physics, dosimetry (both instrumental and personnel), mathematics (college algebra, calculus, and statistics), setting up quality assurance programs, computer programming, word processing, and the use of spreadsheets and data bases. Response: D.R. Sears has received no technical training since 1989. L.H. Key has continued to receive the annual refresher training mandated by his position of Radiological Protection Officer.

l. NIST recommended that we establish an ongoing practice of detailed archival documentation on all equipment used in tests, its calibration and maintenance history, calibration state, and how and by whom calibrated. They stressed that we should document how calculations are performed, with adequate internal documentation of all computer programs employed, and where we obtained the physical and/or conversion constants employed, etc. Response: This is done routinely.

m. NIST recommended that we implement a vigorous, ongoing, real-time documented quality assurance program. In particular, they stressed a requirement that we establish procedures to determine, at the time of every test, that radiation beams had not changed location, intensity (aside from natural decay), and uniformity since the last calibration by Sacramento Army Depot personnel. Response: This is being done routinely.

n. NIST recommended that the practice of recalculating source strength only on a monthly basis be stopped. They suggest that new beam strength values be calculated every day of test or calibration. They used this as an example of the need for everyday availability and use of desk top computers in the offices and at the Blacktail Canyon RADIAC facility. They

commented that we were quite short of computers, and in fact had none at the laboratory until after their first visit here. Response: Two computers have been added to the RADIAC laboratory.

o. NIST suggested that training and peer contact were important to quality assurance and documentation issues. They stated that manpower is undertrained. Without adequate training, we do not know what questions to ask in our efforts to have work performed to expectations at other facilities. NIST provided some examples of potential pitfalls in which a Test Officer and calibration personnel may interpret measurement conditions differently if one or the other party is unaware of the science behind a requirement. Response: Response is in paragraph 1.8k above.

p. NIST recommended that we work toward developing capabilities and procedures which will permit ultimate certification as a secondary or tertiary calibration laboratory. A corollary to this suggestion was the suggestion that we, as well as TECOM (Test and Evaluation Command) and CECOM, move toward adherence to recognized national and international standards (e.g., ANSI, etc.). Response: This recommendation was not pursued, because the equipment and training were unavailable.

q. NIST recommended that a way be found for the RADIAC technical/testing experts at USAEPG to get involved very much earlier in development of MIL-SPEC and Military Standards (MIL-STD) as well as Test Plans. This was because they observed a number of examples in which standards or specs, and corresponding test plans (not of USAEPG authorship) were cut and paste from very old documents, and contained technical errors, ambiguities, or possible obsolete data. Response: RADIAC personnel have not participated in development of MIL-SPEC and MIL-STD as yet.

r. NIST suggested that existing practice leaves a Test Officer little or no discretion to investigate unanticipated results which occur during testing, particularly if the manufacturer has supplied few test items. They suggested that Test Plans should permit such discretion by the Test Officer. Response: The supply of test items continues to be a fundamental limitation, sometimes precluding performance of all tests requested by the Independent Assessment Plan (IAP).

s. NIST suggested that the lack of environmental control of temperature and humidity at the Blacktail Canyon facility is a serious omission, which could have major detrimental impact on test results, and is inconsistent with our mission to test equipment under specified conditions. Both test equipment and test items may exhibit temperature and humidity dependencies. Response: No environmental control has been added.

t. NIST recommended that we verify quantitatively that electromagnetic fields emanating from the front [electromagnetic interference (EMI)] portion of the facility do not alter performance of test items or test and calibration equipment. Response: This work was completed and will be reported in Phase II.

u. Although not part of their mandate, NIST nevertheless recommended that the fence separating RADIAC and EMI be modified to prevent EMI personnel from entering the radiation source Controlled Area. They also referred to the lack of personnel restraint between the Controlled Area and the roof of an adjacent EMI storage area. Response: The gate into the Controlled Area is now secured by chain and padlock, precluding unauthorized entrance by non-RADIAC personnel. The adjacent EMI storage area has been removed.

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SECTION 2. DETAILS OF INVESTIGATION

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INTRODUCTION

In conformance with the agreement between the National Institute of Standards and Technology (NIST) and the U.S. Army Electronic Proving Ground (USAEPG), two visits were made to the Blacktail Canyon Irradiation Facility (BCIF) at Ft. Huachuca, Arizona to evaluate this laboratory for RADIAC instrument testing. The first visit by H. T. Heaton and K.G.W. Inn was made on July 18-19, 1989. The second visit by H. T. Heaton and W. L. McLaughlin was made on January 30-31, 1990. The objectives of the evaluation were to: (1) evaluate the existing equipment and radiation sources at the BCIF which serves as a testing facility for ionizing radiation (e.g., RADIAC) instruments, (2) identify needs for staff training, (3) review the adequacy of support resources at Ft. Huachuca, and (4) review existing voluntary testing and calibration standards related to RADIAC instruments. This report includes material from both visits.

At the USAEPG, the Support Systems Branch, Command and Control Division is responsible for the operations of the Blacktail Canyon Irradiation Facility. The major functions of this Branch are in the areas of ionizing radiation, optics, and intrusion detection. For test requirements other than those relating to ionizing radiation measurement, this Branch cooperates with the Environmental Test Branch, Surveillance and Range Division for environmental testing, EMI & TEMPEST Branch, Electromagnetic Environmental Effect Division for EM interference effects, and the Reliability and Log Supportability Division for factors affecting the reliability of RADIAC instruments. This report will be concerned only with the ionizing radiation activities.

The Support System Branch is responsible for development, first article and acceptance testing of RADIAC equipment; and to a much lesser extent the routine calibration of this equipment. This is done with a very small staff and limited on-site radiation sources. To conduct the required tests, it is often necessary to contract with a military or civilian facility for use of other types of radiation beams.

OBSERVATIONS AT BLACKTAIL CANYON IRRADIATION FACILITY

This section will summarize the staffing, training, equipment, resources, and other factors at the Blacktail Canyon Irradiation Facility which impact on its mission. These observations are based

on visits to the BCIF to see their radiation sources, visits to the technical library at USAEPG, on conversations with the BCIF staff regarding how they conduct their operation, and on examining representative documentation on calibration and testing procedures.

- **Mission/Task**

The process leading to the testing of RADIAC equipment begins with a request by a user for an instrument with specific requirements. A set of military specifications is developed and CECOM (Communication Electronics Command) accepts bids on the specifications. There is a military requirement that CECOM not evaluate the equipment purchased for conformance with the purchase specifications. TECOM (Test and Evaluation Command) is an independent command which preforms this function when requested by CECOM. USAEPG is one laboratory which TECOM could use for the evaluation. The tests are done at Blacktail Canyon Irradiation Facility or at another facility, when test requirements specify radiation fields not on hand. An USAEPG observer is present to personally witness the test when conducted off-site.

USAEPG, Command and Control Division, Support Systems Branch, perform or witness development, first-article testing and acceptance testing for RADIAC equipment. First-article items represent the initial items from the production line used to fulfill the contract. First-article tests include the instrument response to radiation, environmental, mechanical, reliability, and human factor considerations. For the radiation tests, response linearity, accuracy and precision are of major concern. Depending on the test item, the dose range of interest may vary from a mrad to a krad [10 μGy to 10 Gy]. Instrument response may need to be determined for x-ray, gamma-ray, high-energy photon, alpha-particle, beta-particle, or neutron irradiations. The time duration for delivering the dose can range from nanoseconds to steady-state irradiation. Only a few of the radiation sources needed for testing RADIAC instruments are available on-site.

All testing is carried out according to a Test Plan supplied at the beginning of the test. Depending on the location of the tests and the Branch conducting the testing, the TECOM test officer may have little or no input to the Test Plan. As currently implemented, this protocol leaves

virtually no discretion to the test officer to investigate unanticipated results which occur during the test, particularly if the manufacturer supplied only a limited number of test items.

- **BCIF Staffing**

The Support Systems Branch Chief is George A. Broxton. The staff for RADIAC instrument testing consists of two civilians, Dr. D. R. Sears and Larry H. Key, and typically two military personnel.

Dr. D. R. Sears manages the RADIAC testing program, arranges testing at other facilities when necessary, consults with TECOM and CECOM regarding the test plans and conformity to MIL-SPEC, and interpretation of test data. Mr. L. H. Key supervises and trains the Army technicians, conducts the x- and gamma-ray RADIAC tests at USAEPG, maintains the calibration of the radiation sources, serves as the Radiation Safety Officer, complies with Army and the Nuclear Regulatory Commission (NRC) operational directives, and evaluates test data. Army staff assist in the RADIAC tests both on-site and at other facilities, and in the maintenance of the RADIAC sources and equipment.

- **Training**

The senior civilian staff member, Dr. Sears, has a Ph.D. in physical chemistry with little formal training in radiation metrology. However, he has learned (on the job) a considerable amount of the radiation metrology fundamentals needed to conduct the RADIAC testing. The junior staff member, Mr. Key, a high school graduate with several years of intensive working experience at the BCIF laboratory, has many work assignments that are unrelated. This carries him away from radiation measurement assignments a good deal of his time. Also, there seem to be very few opportunities for the appropriate training to improve his expertise in the pertinent radiation metrology needed to fulfill the objectives of the RADIAC program. The two enlisted army technicians are typically E4 or E5 grades and are classified as calibration specialists, MOS 35H. Since maintenance, repair and calibration of RADIAC equipment are outside this MOS description, there is an incentive to request

transfer to a position where they can better maintain their competence in this MOS. Each of the technicians is trained for 90 working days before being allowed to perform tasks independently. This results in inefficiency associated with the periodic training of the newly assigned military personnel and result in assignments to only the simplest tasks.

There is no lack of effort to obtain the required information for successful completion of the assigned mission. However, the depth of expertise to interpret testing information is shallow. The BCIF facility is geographically and professionally isolated from the mainstream of radiation dosimetry facilities in the United States. Virtually no other professional personnel at the base are experienced in this area resulting in little chance for casual conversation to help solve new radiation measurement problems. Further, there is little opportunity to attend professional meetings.

When it is necessary for the test officer to use radiation facilities not at Ft. Huachuca, it is particularly important for the test officer to ask all the necessary questions to ensure that the test facilities, calibration procedures and the radiation quantities reported are actually those specified in the test protocol.

The following examples give three cases where the calibration laboratory and test officer might be interpreting measurement conditions differently. In these examples, the test officer may think that the test plan is being followed but because of the physics behind a particular test measurement, the result may be that the desired RADIAC instrument properties are not measured in the actual test.

1) Conversion from exposure rate to tissue absorbed dose rate.

The x-ray and gamma ray sources at the BCIF are calibrated by personnel from the Sacramento Army Depot in terms of exposure rate measured in roentgens/hour. The BCIF then applies a conversion factor of 0.957 to convert from exposure rate to absorbed dose rate in tissue. There was no available documentation demonstrating the origin of this conversion factor or on the values of the individual components used to calculate absorbed dose rate in tissue. Presumably the absorbed dose rate to tissue, D_t, in rad/hour is calculated from the following equation:

$$D_t = (W/e)*[(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_a]*X$$

where (μ_{en}/ρ) is the mass-energy absorption coefficient for tissue, t, or air, a. X is the measured exposure rate in R/hour, and W/e is the average energy it takes to produce an ion pair in air. The latest ICRU recommended value for W is given in ICRU 31 (Average Energy Required to Produce an Ion Pair, 1979) as 33.85 eV per ion pair in dry air. In 1985, BIPM (M. Boutillon and A.-M. Perroche, "Effect of charge stopping-power values on the W values recommended by the ICRU for electrons in dry air," Bureau International des Poids et Mesures, Report CCEMRI(I)/85-8) reanalyzed the data in the ICRU report and recommended a value of 33.97 eV per ion pair. Using Hubbell's data ("Photon Mass Attenuation and Energy-absorption Coefficients from 1 keV to 20 MeV," **Int. J. Appl. Radiat. Isot.** 33, (1982), 1269-1290) for the mass-energy absorption coefficients in tissue, the values of (μ_{en}/ρ) for ^{137}Cs and ^{60}Co are:

TABLE 1. (μ_{en}/ρ) values (in units of $cm^2\ g^{-1}$)

	^{137}Cs	^{60}Co
tissue	0.03233	0.02934
air	0.02935	0.02663

Using the latest values, the conversion factor from exposure rate to absorbed dose rate in tissue is calculated to be 0.9647 for Cs and 0.9649 for Co. These values are about 0.8% higher than the values presently used at BCIF.

2) Dosimeters irradiated "free-in-air" vs. on-phantom.

The U. S. Nuclear Regulatory Commission requires that all radiation workers use a personnel dosimetry service accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). To be accredited under this program, the personnel dosimetry processor

must read a series of dosimeters irradiated by the testing laboratory within a precision and bias specified in ANSI N13.11-1983, ["American National Standard for Dosimetry - Personnel Dosimetry Performance Criteria for Testing," American National Standards Institute, New York, NY]. This standard requires that the personnel dosimeters be irradiated on a phantom of tissue-like material (i.e., plastic). The standard also specifies the factor, C_x, for conversion from exposure to dose equivalent in a number of x-ray beams and for ^{137}Cs gamma rays. These are given in the following table.

Table 2. Conversion factors (C_x) from exposure to dose equivalent

	X-rays	
Beam HVL	shallow	deep
0.36	0.92	0.40
1.02	1.02	0.72
1.86	1.14	0.95
2.79	1.14	0.98
5.03	1.30	1.20
10.25	1.43	1.38
	^{137}Cs	
	1.03	1.03

For gamma rays, the dose equivalent is the same as the tissue-absorbed dose. However, the conversion factors specified in this table include the dose due to gamma rays backscattered from the phantom (i.e., body) and detected by the dosimeter as well as a correction to a specified depth in the phantom. From this table, it can be seen that there is considerable variation in the C_x factors, particularly for x-rays. Even for ^{137}Cs, the deep dose (1 cm) conversion factor, 1.03, is 7.6% different than the value for the conversion factor presently used by the BCIF.

This raises two questions. The first is, for monitors worn on the body by field personnel, does the absorbed dose include the effects of scatter and attenuation in the body or the "free-in-air" exposure and absorbed dose to tissue conversion factor? The second point is concerned with irradiations to RADIAC devices which are similar to personnel dosimeters. If these irradiations are done at facility which is normally concerned with determining the dose to personnel dosimeters, then it is the responsibility of the test officer to ensure that both the irradiation of the device is done on the phantom and that the appropriate conversion factor is used. For example, if the "free-in-air" conversion factor is desired, then the device should be irradiated with minimal support and the conversion factor in example 1 should be used; however, if a more realistic dose estimate is desired, then the device should be irradiated on a phantom and the corresponding value of C_x should be used.

3) Neutron irradiations.

For neutrons the absorbed dose to tissue is not equal to the dose equivalent. These two quantities differ by the quality factor which is dependent on neutron energy. If the spectrum is not known, it is typically assigned a value of 10. Thus, if one is developing a test protocol for a RADIAC device which detects neutrons, one needs to be very careful whether one is interested in dose equivalent (appropriate for personnel radiation protection measurements) or absorbed dose to tissue (appropriate for estimating the effects of high level, acute doses). If the device may be used for both applications, either now or in the future, then it will be necessary to develop a test protocol in which the response of the device for both quantities is determined.

When using neutrons to study instrument response, the quantity most often measured by the calibration ('esting) aooratory is fluence. Thus it is necessary to use a conversion factor to determine either the absorbed dose to tissue or the dose equivalent. Both of these

require an integration over neutron energy of the true fluence from the neutron source times the desired conversion factor per unit energy interval.

If the monitor used to measure the neutron fluence has a threshold, the absorbed dose below the threshold will not be accounted for in the fluence measurement. This is the case for activation foils commonly used to determine the neutron fluence. If the device being tested responds to neutrons with energies lower than the threshold, the calibration laboratory will have to make a correction to the calculated dose. This requires that the calibration laboratory have a detailed knowledge of the entire spectrum from the neutron source. Since the calibration laboratory may not normally be interested in the contribution from the low energy neutrons, it is the responsibility of the test officer to make sure that the calibration laboratory has properly accounted for this component if the device under test might respond to these neutrons. The details of the calculations used to make the correction should be documented.

- **Equipment**

The Blacktail Canyon Irradiation Facility is about 7 miles from the Support System Branch offices. The facility occupies the rear portion of a fenced-in building which it shares with the EM Interference Test Facility. There is no control of environmental parameters such as temperature, pressure, and humidity in this building. For a testing laboratory concerned with verifying the response of instruments under specific conditions, the lack of environmental control could have a major detrimental impact on the measured results. Besides the direct impact of the lack of controlled environmental conditions on the instruments during the radiation tests, there are also indirect effects as personnel in the building try to control its environment. For example, when the radiation sources are not in use during the summer months, the door in the rear of the radiation area has been left open in an effort to control the environmental conditions in the building.

There were control panels for building systems in the Radiation Controlled Area, but new control panels are now located and accessible outside this area. The gate to the controlled area is secured with a chain and padlock. However, the fence around the Controlled Area does not extend to the ceiling. Additionally, the personnel restraint on the roof of the storage area next to the Controlled Area serves more as a warning not to enter rather than as a positive restraint to prevent entry. Thus it would not be difficult for personnel occupying the front half of the building to enter the Controlled Area if they perceived the need to do so.

The radiation sources at the Blacktail Canyon Irradiation Facility consist of: A Shepherd model 138 dual irradiator with 650 Ci ^{137}Cs and 100 Ci ^{60}Co; 120 Ci ^{137}Cs [UDM-1A]; 11 Ci ^{60}Co [UDM-1]; a Shepherd model 178 PuBe neutron source; several small miscellaneous sources; 400 kVp constant potential x-ray unit; a 150 kVp x-ray unit. These are the nominal values of the sources at the time they were loaded into the irradiators and have not been corrected for radioactive decay to their present values. The gamma sources produce a collimated beam (i.e., a fraction of 4π geometry) of radiation. There is a horizontal track system with an instrument table so that instruments can be placed at various distances to achieve the desired exposure rates. The x-ray units are in a shielded container which functions as a cabinet x-ray system. It operates in a vertical beam mode. Different beam qualities are achieved by inserting various thicknesses of filter material in the beam and by operating the x-ray unit at different potentials. Different exposure rates are achieved by varying the x-ray tube current.

Once a year, personnel from the Nucleonics Laboratory at Sacramento Army Depot come to the BCIF to calibrate all the radiation sources. For the x-ray and gamma-ray sources this calibration is in terms of exposure rate at various specified distances. As previously indicated, personnel at the BCIF use a conversion factor to convert from exposure rate to absorbed dose rate in tissue. The sources are corrected for decay only on a monthly basis.

There is one small environmental chamber in the Controlled Area used for studying the response of the test instruments to different conditions. However, simultaneous radiation and environmental tests are seldom required in existing test procedures. For the routine environmental tests specified in the test procedure, the USAEPG uses the Environmental Test Branch located at Ft. Huachuca.

There was one recently installed personal computer (PC) at the calibration facility. The staff is still determining the best procedures for implementing this into routine operation. For all but the simplest operations at the lab, PCs facilitate calculations of exposure calibrations, keep record of past quality control/quality assurance program results to make sure that the system is still in statistical control, and keep track of the test results made at the facility. There is still a lack of office-use PC's for this branch.

For those tests which require equipment not available at Ft. Huachuca, facilities elsewhere are required. Therefore, a considerable amount of Dr. Sears' time is spent traveling in conducting these tests. This results in loss of control over experiment, lost time, less familiarity with the working of the equipment and radiation sources, and less than optimum testing conditions.

- **Documentation**

The main documentation at the facility was the calibration reports supplied by Sacramento and plots of the variation of exposure rate versus source-detector distance derived from these reports. There was no documentation on the conversion factors used to calculate absorbed dose rate in tissue from exposure rate, or on the details of exactly what the former actually meant. In particular, there was no documentation on investigations to determine the effect of RF and EM radiation from sources in and around the building. The concern with the effects of the EM radiation is more important for active RADIAC equipment (e.g., instruments) than for passive RADIAC equipment (e.g., dosimeters).

- **Quality Control/Quality Assurance**

The on-site testing facility does not have in-house quality control/quality assurance programs to assure that the radiation beams are behaving the same way as when they were calibrated by Sacramento personnel. There is no documentation that could be used in court if the manufacturer of the test item challenged their test results through litigation. The use of quality control/quality assurance programs is gaining prominence as a standard operating procedure for calibrating and testing ionizing radiation equipment.

- **Resources**

This section will limit the discussion of resources to funding and the base library.

1) Funding

Funding is adequate but there is little flexibility for upgrading equipment and metrology development. One problem is that there is little base support for the group. All funding is to come out of funds required to perform specific tests. Manpower is adequate for the present mode of operation but undertrained. Equipment and physical facilities are adequate for some categories of testing, but substantial travel to other facilities is required for some requested tests, and for attendance at suitable training courses.

2) Library

The library at this base is grossly inadequate in terms of providing appropriate literature for calibrating or testing ionizing radiation instruments. There are a few general textbooks pertaining to ionizing radiation measurement. However, there are no textbooks or publications on specific aspects dealing with this subject, nor any periodic journals in fields related to this topic.

- **Safety**

Our first impression is that radiation related operations at Blacktail Canyon Irradiation Facility are conducted in a reasonable and safe manner. It is to our surprise, however, that this Army base does not have a Health Physicist on its staff to monitor, consult, and guide radiation safety practices. Concerns regarding the personnel fence around the radiation sources were discussed earlier.

The Army has NRC general and special radioactivity source licenses. Since this is a Federal facility, Food and Drug Administration does not require notification of installation of the x-ray unit and the State of Arizona does not have the authority to require a specific license.

RELATIONSHIP OF FT. HUACHUCA AND THE NATIONAL MEASUREMENT SYSTEM

For a number of years the National Institute of Standards and Technology, formally the National Bureau of Standards, has been advocating a system of Secondary-level and Tertiary-level laboratories in the private, state, and federal sectors. [See Requirements for an Effective National Ionizing Radiation Measurements Program, **NBS SP 603** (1981) and E. H. Eisenhower, "Measurement Quality Assurance," Health Physics, **55** (1988), p. 207-213.] These programs have certain common elements: (1) Secondary-level laboratories will be accredited by appropriate nationally recognized organizations. They will be accredited using written accreditation criteria. (2) Accredited laboratories must have written documentation for their internal procedures. (3) The secondary-level laboratories must participate in a periodic Measurement Quality Assurance (MQA) proficiency test conducted by the NIST. The tertiary-level laboratories must participate in a similar proficiency test conducted by a secondary-level laboratory. (4) The laboratories must have an in-house quality control program in place which monitors the performance of all the critical pieces of calibration equipment to make sure that its variation is within expected, and acceptable, statistical limits. To date all of the accreditation criteria have been developed for laboratories calibrating ionizing radiation equipment. However, it is expected that when the system is fully operational that the criteria will be expanded to include testing laboratories.

At present, the Army is planning to have a single secondary-level laboratory for calibrations of ionizing radiation instruments. It will be located within the U. S. Army Primary Standards Laboratory; Test, Measurement, and Diagnostic Equipment Support Group at Redstone Arsenal in Alabama. For the federal sector, there are no criteria for tertiary-level laboratories at present. (This program is in the initial stages of implementation; no secondary-level laboratories have yet been accredited to test prospective tertiary-level laboratories.) It is expected that the criteria for the tertiary-level laboratories will be similar to the secondary-level laboratories but will have less restrictive operational requirements. For the requirements of the laboratories in this system refer to Appendix B, which includes the latest draft of the federal sector accreditation criteria. For the federal sector laboratories, the accreditation organization will be the National Voluntary Laboratory Accreditation Program (NVLAP) located at NIST.

When this program is fully implemented, it is assumed that the BCIF will become one of the accredited laboratories. While the Army has identified the secondary-level laboratory for calibrating ionizing radiation instrument, it has not stated if the same laboratory will also be the only secondary-level laboratory for testing ionizing radiation instruments. Hence, several levels at which Ft. Huachuca could participate in the overall program are listed.

1) Limited Army facility. This is the present mode of operation. There is a small staff, limited radiation sources, limited chambers for making measurements in different environments, few technical resources, and limited interactions with technical personnel from other major facilities involved with ionizing radiation instruments.

2) Regional facility. This would involve more radiation sources with automatic mechanisms for controlling the amount of radiation, some automated data taking and analysis, the capability to do most measurements in-house, and in-house staff with expertise in radiation measurements at least for the in-house radiation sources.

3) State-of-Art or Prime Army facility for Instrument testing. This would involve having all the radiation sources necessary for complete testing, equipment to completely calibrate these sources, and in-house staff expert in all aspects of radiation measurements.

RECOMMENDATIONS

Before specific recommendations on new equipment and staffing requirements can be made, the exact role of the Blacktail Canyon Irradiation Facility as a testing facility in the National Measurement System described in the previous section must be defined. The following recommendations only address elements for a minimum upgrade and hence are applicable to all the options outlined above.

- **Mission/Task**

The whole testing process would probably be better served if the testing branch could provide expert advice to the contracting unit and end user for writing of the technical specifications and testing protocols. The MIL-SPECs and testing protocols should be evaluated by technical experts for applicability and adequateness to provide the army with the information upon which it can evaluate first article testing. Including these two steps in the process of generating MIL-SPECs would help insure optimum and meaningful test measurements. Often these specifications appear to be "cut and paste" documents from previous specifications and do not necessarily represent current testing or radiation calibration techniques and philosophies. At a minimum, the specifications should use the national and international standards that pertain to radiation instruments to establish the minimum criteria that an instrument must meet in the test procedure.

Peer review is an important means of providing new, improved ideas and alternative approaches to technology development. In the area of ionizing radiation, detailed reviews of the equipment and procedures at the BCIF (at least every other year), would help keep USAEPG

expertise current. These peer review teams should interact directly with higher levels of management to: 1) provide updated information on quality of work being done, 2) emphasize aspects of the work being done well, and 3) stress areas where improvement is needed.

- **BCIF Staffing**

For the present mode of operation the present number of staff appears to be adequate. However, the staff is responsible for too many unrelated tasks. There is rapid turnover among the Army staff which requires continual training for their replacements. The time spent by the permanent staff on Army staff retraining could be more efficiently spent engaged in the primary responsibility of testing RADIAC instruments.

- **Training**

As noted, this facility is geographically and professionally isolated from the mainstream of radiation dosimetry facilities in the United States. Hence, strategies must be adopted to provide opportunities for the present personnel to improve their knowledge of both practical and theoretical aspects of radiation dosimetry. Possible strategies to improve depth of expertise would include: formal class work at a nearby university or junior college, attending pertinent conferences; active membership in professional societies (e.g., Health Physics Society [HPS], Institute of Electrical and Electronic Engineers [IEEE], American Nuclear Society [ANS], American Association of Physicists in Medicine [AAPM]); enrollment in short courses and continuing education courses offered by professional societies; visits to other laboratories to discuss and compare methods and techniques; consultation with leading experts; and participation on national standards committees (American National Standards Institute [ANSI], American Society for Testing and Materials [ASTM]), international standards committees (International Electrotechnical Commission [IEC], International Standards Organization [ISO], Deutsche Industrie Norm [DIN]), participation in writing accreditation

criteria for instrument calibration laboratories (HPS, Conference of Radiation Control Program Directors [CRCPD], National Voluntary Laboratory Accreditation Program [NVLAP], British Calibration Service [BCS]), review of reports from national and international testing laboratories (Battelle Pacific Northwest Laboratory [BPNW], National Radiation Protection Board [NRPB], Physikalish-Technische Bundesanstalt [PTB]), participate on voluntary standards writing groups; participate with intra-service groups concerned with RADIAC instruments (Calibration Coordination Group); and independent reading of technical literature.

Topics which would be useful for personnel at this facility include: nuclear physics, radiation physics, dosimetry (both instrumental and personnel), mathematics (college algebra, calculus, statistics), setting up quality assurance programs, and computer programs (fundamentals of operating system, word processing, spreadsheets [e.g., Lotus 123], data bases [e.g., dBASE]).

Opportunities for specific training courses continually change and listing specific courses would be out of date virtually as soon as this report is issued. Hence, rather than recommend specific courses at particular institutions, this report will list only representative references announcing the availability of courses and some organizations specializing in courses related to ionizing radiation:

1) Continuing Education and Special Topic courses presented at the annual meeting of the Health Physics Society (HPS). Information on the annual meeting can be obtained from:

Health Physics Society
8000 Westpark Drive
Suite 400
Mclean, VA 22102

or from the Health Physics or The Health Physics Society Newsletter both published by the HPS. The news letter also lists many courses sponsored by other organizations on ionization radiation.

2) Refresher Courses are presented at the annual meeting of the American Association of Physicist in Medicine. Information on the annual meeting can be obtained from:

American Association of Physicists in Medicine
335 E. 45th Street
New York, NY 10017

or from Medical Physics published by the AAPM.

3) The publication Physics in Medicine and Biology also publishes meetings and short courses related to ionizing radiation.

4) The Army also conducts radiation courses at

U.S. Army Chemical School
Edwin R. Bradley Radiological Laboratories
Fort McClellan, AL 36205

5) Oak Ridge Associated Universities
Professional Training Programs
P. O. Box 117
Oak Ridge, TN 37831-0117

6) Harvard School of Public Health
Office of Continuing Education
677 Huntington Drive
Boston, MA 02115

7) Massachusetts Institute of Technology
Director of Summer School
Rm E19-356
Cambridge, MA 02139

8) Technical Management Services, Inc.
P. O. Box 16
New Hartford, CT 06057

- **Equipment**

For the present mode of operation, the existing radiation sources appear to be adequate. The x-ray units are "cabinet" in design so the scatter component cannot be readily determined. Hence the effect of this scattered radiation on the test procedure cannot be properly assessed. Thus, this equipment can be used for general radiographic work but it should not be used for type testing of instruments which require accurate knowledge of the delivered dose unless extensive studies are made to quantify and document the actual x-ray beams. Unless the beam quality for each of the x-ray beams is accurately known, it is not possible to properly characterize the radiation field. Since there is no in-line beam monitor to determine the total exposure delivered, it is estimated from the x-ray current and voltage indicators on the x-ray control unit. While this is satisfactory for general purpose radiography, it is not adequate for first article type testing of instruments.

There should be more in-house instrumentation for both x-ray and gamma ray sources to verify the exposure rate from the radiation sources particularly if questions arise between the regular calibrations done by Sacramento personnel. This should include an ion chamber and electrometer system which is calibrated either at the same time the radiation sources are calibrated or sent back to the calibration laboratory for calibration. If the latter option is used, the radiation field for one of the gamma sources should be determined with the instrument before shipping and after its return from the calibration laboratory to ensure that there was no change in the instruments response during shipping. The BCIF presently possesses a Victoreen electrometer and several ion chambers but these are not used in a routine manner to verify the consistency of source output.

The effect of EM radiation fields generated at this army base on the testing of ionizing radiation instruments needs to be determined and documented. If this radiation interferes with any test procedure specified for testing a specific RADIAC device, it will be necessary the install RF shielding in the portion of the building devoted to ionizing radiation irradiations.

The lack of control of the basic environmental conditions at the lab site, e.g., temperature and humidity, is a serious problem for a facility with a requirement to test instruments at the specified conditions. Steps should be taken to correct this deficiency.

Once purchased, all equipment is expected to last forever and not need updating. For example, the obsolete TLD readers and smear counter are not calibrated, infrequently used, and probably not reliable (no effort or desire made to make them useful). Mechanisms need to be established whereby obsolete equipment would routinely be replaced by current models. Possibly this could be achieved by some depreciation fee attached to all tests performed by BCIF personnel.

- **Documentation**

There needs to be documentation on in-house quality control/ quality assurance procedures, measurements made to understand how laboratory equipment and radiation sources affect calibrations or tests of instruments, conversion factors used to go from calibrated quantities to test quantities, how the equipment and sources are calibrated, etc.

There should be more documentation on how calibrations and testing done off-site are carried out and monitored. The present documentation of the procedures used on-site and off-site to verify the radiation fields used in the test procedure is inadequate and should be a high priority action item to improve this documentation. The documentation should include details of how the facility determined its reference radiation field, calibration techniques used, date of the last calibration, quality assurance procedures to make certain that reference radiation fields are still in statistical control, details on corrections to determine the reference radiation field and the impact of these corrections on the present calibration or test measurement, and conversion factors used to convert the reference radiation field to absorbed dose in tissue.

The existing Test Operating Procedures (TOP) are dated. They should be completely revised and updated to reflect current technology and should define and use up-to-date, or at least consistent, radiation quantities and units.

- **Quality Assurance/Quality Control**

At present, calibration of RADIAC instruments is dependent on the capabilities and expertise possessed by the USAEPG's Calibration Group. To give credibility to the test results, quality control and quality assurance procedures must be developed for the critical pieces of equipment used and the procedures must be documented. This applies both to on-site and off-site measurements.

Quality assurance and quality control programs are corners stones for providing credibility to measurements made between calibrations. It is essential that these programs be in place for any laboratory with the responsibility of making tests on equipment for the purposes of accepting or rejecting items based on performance criteria and test procedures.

- **Resources**

1) Funding

The present method of obtaining funding from CECOM provides little flexibility for upgrading metrology. Additional resources must be sought to maintain expertise at this laboratory.

One possible approach to obtain additional funding to maintain expertise in the area of ionizing radiation would be for USAEPG to consider adding a "Development Fee" as part of the cost of doing tests for CECOM, and use the funds for metrology improvement.

2) Library

The library is inadequately stocked with technical resources necessary for RADIAC work. There are no periodic journals concerned with radiation dosimetry or radiation instrument testing. Likewise, there are no textbooks on this subject. Thus, if questions arise on the principles of operations of instruments, on technical matters regarding a particular test procedure, on the definition of a particular radiation quantity, etc., there is no on-site

reference material in which to search for the answers. Additional resources must be found to better stock the library in order for staff to keep abreast with technological advances in the field of ionizing radiation.

A list of technical references that should be available at the library is given in Appendix A of this report. This list is typical of the type of reference material which must be available to a facility testing or calibrating ionizing radiation instruments.

Since both the BCIF and the new offices are physically located at large distances from the existing library, consideration should be given to establishing a satellite library in the building housing the new offices.

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SECTION 3. APPENDICES

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APPENDIX A

TECHNICAL REFERENCE MATERIAL

The following list of technical references are typical of the type which should be available to personnel both in an instrument testing facility or a laboratory calibrating ionizing radiation instruments. This list is representative and should not be considered all inclusive. Thus, it is not necessary for the library to obtain everyone of these references, however, it should possess the vast majority. Since the reference material cited in this appendix is intended for the library, articles dealing with measurement of ionizing radiation appearing in journals are specifically excluded.

Most U. S. Government issued publications are available from either the issuing agency or from:

National Technical Information Service
U. S. Department of Commerce
Springfield, VA 22161

Textbooks

Andrews, H. L., **Radiation Biophysics**, 2nd Ed., Prentice-Hall, Englewood Cliffs, NJ, (1974)

Attix, F. H., **Introduction to Radiological Physics and Radiation Dosimetry**, John Wiely & Sons, New York, NY, (1986)

Attix, F. H. and W. C. Roesch, **Radiation Dosimetry**, Vol 1 Fundamentals, 2nd Ed., Academic Press, New York, NY, (1968)

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Attix, F. H. and E. Tochilin, **Radiation Dosimetry**, Vol 3 Sources, Fields, Measurements, and Applications, 2nd Ed., Academic Press, New York, NY, (1969)

Attix, F. H., **Topics in Radiation Dosimetry, Radiation Dosimetry Supplement 1**, Academic Press, New York, NY, (1972)

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Cember, H., **Introduction to Health Physics**, Pergamon Press, Oxford, (1969)

Eichholz, G. G. and J. W. Poston, **Principles of Nuclear Radiation Detection**, Ann Arbor Science, Ann Arbor, MI, (1979)

Evans, R. B., **The Atomic Nucleus**, McGraw-Hill, New York, NY, (1955)

Greening, J. R., **Fundamentals of Radiation Dosimetry, Medical Physics Handbook 6,** Adam Hilger Ltd., Bristol, (1981)

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** Horowitz, Y. S., **Thermoluminescence and Thermoluminescence Dosimetry**, Volumes I, II, and III, CRC Press, Boca Raton, FL

Johns, H. E. and J. R. Cunningham, **The Physics of Radiology**, 4th Ed. Charles C Thomas,Springfield, IL, (1983)

Kase, K. R., B. E. Bjarngard, and F. H. Attix, **The Dosimetry of Ionizing Radiation**, Vol 1, Academic Press, Inc., New York, NY, (1985)

Kase, K. R., B. E. Bjarngard, and F. H. Attix, **The Dosimetry of Ionizing Radiation**, Vol 2, Academic Press, Inc., New York, NY, (1987)

Kase, K. R. and W. R. Nelson, **Concepts of Radiation Dosimetry**, Pergamon Press, Oxford, (1978)

Kiefer, H. K. and R Maushart, **Radiation Protection Measurement**, Pergamon Press, Oxford, (1972)

Knoll, G.F., **Radiation Detection and Measurement**, 2nd Ed., John Wiely & Sons, New York, NY, (1989)

Lalos, G., **Calibration Handbook: Ionizing Radiation Measuring Instruments**, Calibration Coordination Group DOD, Joint Technical Coordination Group for Metrology and Calibration (1983)

Mann, W. B., A. Rytz and A. Spernol, **Radioactivity Measurements - Principles and Practice**, Pergamon Press, Oxford (1990)

McLaughlin, W. L. (Ed.) "Trends in Radiation Dosimetry," Applied Radiation and Isotopes, 33 (No. 11), Pergamon Press, Oxford, (1982)

McLaughlin, W. L., A. W. Boyd, K. N. Chadwick, J. C. McDonald and A. Miller, **Dosimetry for Radiation Processing**, Taylor and Francis, London (1989)

IAEA Publications

A list of current publications is available from:

UNIPUB
P. O. Box 433
Murray Hill Station
New York, NY 10016

SM 222: National and International Standardization of Radiation Dosimetry (1978)

TR 107: Neutron Fluence Measurements (1970)

TR 109: Personnel Dosimetry System for External Radiation Exposures (1970)

TR 133: Handbook on Calibration of Radiation Protection Monitoring Instruments (1971)

TR 150: Measurement of Short- Range Radiation (1973)

TR 185: Calibration of Dosemeters Used in Radiotherapy (1979)

TR 188: Radiological Safety Aspects of the Operation of Electron Linear Accelerators (1979)

ICRU Publications

A list of current publications is available from:

International Commission on Radiation Units and Measurements
7910 Woodmont Avenue
Bethesda, MD 20184

The entire ICRU publication series is useful and in particular the following publications:

10b: Physical Aspects of Irradiation (1964)

13: Neutron Fluence, Neutron Spectra and Kerma (1969)

14: Radiation Dosimetry: X Rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 50 MeV (1969)

17: Radiation Dosimetry: X Rays Generated at Potentials of 5 to 150 kev (1970)

20: Radiation Protection Instrumentation and Its Application (1971)

23: Measurement of Absorbed Dose in a Phantom Irradiated by a Single Beam of X or Gamma Rays (1973)

24: Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures (1976)

26: Neutron Dosimetry for Biology and Medicine (1977)

28: Basic Aspects of High Energy Particle Interactions and Radiation Dosimetry (1978)

29: Dose Specifications for Reporting External Beam Therapy with Photons and Electrons (1979)

30: Quantitative Concepts and Dosimetry in Radiobiology (1979)

31: Average Energy Required to Produce an Ion Pair (1979)

33: Radiation Quantities and Units (1980)

34: The Dosimetry of Pulsed Radiation (1982)

35: Radiation Dosimetry: Electron Beams and Energies Between 1 and 50 MeV (1984)

37: Stopping Powers for Electrons and Positrons (1984)

39: Determination of Dose Equivalents Resulting from External Radiation Sources (1985)

40: The Quality Factor in Radiation Protection (1986)

NCRP Publications

A list of current publications is available from:

National Council on Radiation Protection and Measurements
7910 Woodmont Avenue
Bethesda, MD 20184

The entire NCRP publication series is useful and in particular the following publications:

23: Measurement of Neutron Flux and Spectra for Physical and Biological Applications (1960)

25: Measurement of Absorbed Dose of Neutrons and Mixtures of Neutrons and Gamma Rays (1961)

38: Protection Against Neutron Radiation (1971)

49: Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays for Energies Up to 10 MeV (1976)

50: Environmental Radiation Measurements (1976)

51: Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities (1977)

SP 250 -16: Lamperti, P. J., T. P. Loftus and R. Loevinger, NBS Measurement Services: Calibration of X-Ray and Gamma-Ray Measuring Instruments (1988)

SP 250 -18: McGarry and E. W. Boswell, NBS Measurement Services: Neutron Source Strength Calibrations (1988)

SP 250 -19: Weaver, J. T., T. P Loftus, and R. Loevinger, NBS Measurement Services: Calibration of Gamma-Ray Emitting Brachytherapy Sources (1988)

SP 250-21: Pruitt, J. S., C. G. Soares and M. Ehrlich, NBS Measurement Services: Calibration of Beta-Particle Radiation Instrumentation and Sources (1988)

SP 300-1: Ku, H. H., (ed.), Precision Measurement and Calibration (1969)

SP 456: Fivozinsky, S. P., (ed.), Measurements for the Safe Use of Radiation (1976)

SP 554: Heaton, II, H. T., and R. Jacobs, (eds.), Proceedings of a Conference on Neutrons from Medical Accelerators (1979)

SP 603: Requirements for an Effective National Ionizing Radiation Measurements Program (1981)

SP 609: Heaton, II, H. T. (ed.), Proceedings of a Meeting on Traceability for Ionizing Radiation Measurements (1982)

SP 633: Schwartz, R. B. and C. M. Eisenhauer, Procedures for Calibrating Neutron Personnel Dosimeters (1982)

DOE Reports

BNWL1991: Bramson, P.E., B. V. Andersen, D. M. Flemming, R. L. Kathern, O. R. Mulhern, C. E. Newton, E. E. Oscarson, and J. M. Selby, Technological Considerations in Emergency Instrumentation Preparedness (1976)

EH-0026: Handbook for the Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems (1986)

EH-0027: Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems (1986)

ID-12104: Carlson, R. D. and T. F. Gesell, The Department of Energy Laboratory Accreditation Program in Personnel Dosimetry: Results of the Pilot Performance Test (1986)

ID-12106: Quality Assurance Manual for the Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems (1987)

PNL-5813 Pt.2: Keynoyer, J. L., K. L Swinth, G. A. Stoetzel, and J. M. Selby, Performance Specifications for Health Physics Instruments - Portable Instrumentation for Use in Normal Work Environments; Part 2: Test Results

PNL-SA-13346: Selby, J. M., K. L. Swinth, E. J. Vallario, and B. L. Murphy, Proceedings of the Workshop on Radiation Survey Instruments and Calibrations (1985)

PNL-SA-15004: Swinth, K. L. and E. J. Vallario, Proceedings of the Department of Energy Workshop on Beta Measurements (1987)

NUREG Reports

These NUREG documents are available from:

NRC/GPO Sales Program
U. S. Nuclear Regulatory Commission
Washington, DC 20555

1156: Brodsky, A., Accuracy and Detection Limits for Bioassay Measurements in Radiation Protection, Statistical Considerations

CP-0050: Proceedings of the International Beta Dosimetry Symposium (1984)

CR-3296: Sherbini, S., and S. W. Porter, A Review of the Current Deficiencies in Personnel Beta Dosimetry, With Recommendations (1983)

CR-3775: Eisenhower, E. H., Quality Assurance for Measurements of Ionizing Radiation (1984)

CR-4266: Ehrlich, M., J. S. Pruitt, C. G. Soares, C. E. Dick, H. T. Heaton, II, and R. B. Schwartz, Standard Beta-Particle and Monoenergetic Electron Sources for the Calibration of Beta-Radiation Protection Instrumentation (1985)

ANSI Standards

A catalog of current American National Standards is available from:

American National Standards Institute
1430 Broadway
New York, NY 10018

They also publish "ANSI Standards Action" which is a newsletter on proposed and recently issued ANSI, ISO, and IEC standards.

The ANSI standards listed below are particularly relevant to organizations calibrating or testing ionizing radiation measuring instruments. As these standards are revised, reaffirmed, or withdrawn every 5 years, the ANSI catalog should be consulted for the latest version.

N13.3:	Dosimetry for Criticality Accidents
N13.4:	Specification of Portable X- or Gamma- Radiation Survey Instruments
N13.5:	Performance Specifications for Direct Reading and Indirect Reading Pocket Dosimeters for X- and Gamma Radiation
N13.7:	Criteria for Film Badge Performance
N13.10:	Specification and Performance of On-site Instruments for Continuously Monitoring Radioactivity in Effluents
N13.11:	for Dosimetry - Personnel Dosimetry Performance - Criteria for Testing
N13.15:	for Radiation Detectors - Personnel Thermoluminescence Dosimetry Systems - Performance
N13.27:	Performance Requirements for Pocket-sized Alarm Dosimeters and Alarm Ratemeters
N42.1:	Test Procedure for Semiconductor Radiation Detectors (for ionizing radiation)
N42.13:	Calibration and Usage of "Dose Calibrator" Ionization Chambers for the Assay of Radionuclides
N42.14:	Calibration and Usage of Germanium Detectors for Measurement of Gamma-ray Emission of Radionuclides
N42.17A:	Performance Specifications for Health Physics Instrumentation - Portable Instrumentation for Use in Normal Environmental Conditions

N42.17B: Performance Specifications for Health Physics Instrumentation - Occupational Airborne Radioactivity Monitoring Instruments

N42.17C: Performance Specifications for Health Physics Instrumentation - Portable Instrumentation for Use in Extreme Environmental Conditions

N42.2: IEEE Standard Test Procedures for Amplifiers and Preamplifiers for Semiconductor Radiation Detectors for Ionizing Radiation

N42.3: American National Standard and IEEE Standard Test Procedure for Geiger-Muller Counters

N42.7: IEEE Standard: Criteria for Protection Systems for Nuclear Power Generation Stations

N42.8: IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors

N42.9: IEEE Standard Test Procedures for Photomultipliers and Scintillation Counting and Glossary for Scintillation Counting Field

N43.1: Radiological Safety in the Design and Operation of Particle Accelerators

N43.4: General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV

N43.5: Radiological Safety Standard for the Design of Radiographic and Fluoroscopic Industrial X-Ray Equipment

N43.6: Sealed Radioactive Sources, Classification

N43.9: Radiological Safety for Design and Construction of Apparatus for Gamma Radiography

N319: Personnel Neutron Dosimeters (Neutron Energies Less Than 20 MeV)

N320: Performance Specifications for Reactor Emergency Radiological Monitoring Instrumentation

N323: Radiation Protection Instrumentation Test and Calibration

N449: Procedures for Periodic Inspection of Cobalt-60 and Cesium-137 Teletherapy Equipment

N545: Performance, Testing and Procedural Specifications for Thermoluminescence Dosimetry (Environmental Applications)

ASTM Standards

A catalog of American Society for Testing and Materials standards is available from:

ASTM
1916 Race Street
Philadelphia, PA 19103

Away Practice for Calculating Absorbed Dose From Gamma or X Radiation

E668 Practice for the Application of Thermoluminescence-Dosimetry (TLD) systems for Determining Absorbed Dose in Radiation-Hardness of Electronic Devices

E1026 Standard Practice for Using Fricke Reference Standard Dosimetry System

E1204 Practice for Application of Dosimetry in the Characterization and Operation of a Gamma Irradiation Facility for Food Processing

E1205 Test Method for Using Ceric-Cerous Sulfate Dosimeter to Measure Absorbed Dost in Water

E1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources

E1250 Method for Application of Ionization Chambers to Assess Low Energy Gamma Component of Cobalt-60 Irradiations Used in Radiation-Hardness Testing of Silicon Electronic Devices

E1261 Guide for Selection and Application of Dosimetry Systems for Radiation Processing of Food

E1275 Practice for Use of a Radiochromic Film Dosimetry System

E1276 Practice for Use of a Polymethylmethacrylic Dosimetry System

ISO Standards

ISO standards are international standards issued by the International Organization for Standardization. They are available from ANSI.

1710 Fundamental Principles for Protection in the Design and Construction of Installations for Work on Unsealed Radioactive Materials

4037 X and γ Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining their Response as a Function of Photon Energy

4037/Addendum 1 X and γ Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining their Response as a Function of Photon Energy; Addendum 1: High Rate Series of Filtered X-Radiations

6980 Reference Beta Radiations for Calibrating Dosemeters and Doseratemeters and for Determining Their Response as a Function of Beta Radiation Energy

8529 Neutron Reference Radiations for Calibrating Neutron-Measuring Devices used for Radiation Protection Purposes and for Determining Their Response as a Function of Neutron Energy

8769 Reference Sources for the Calibration of Surface Contamination Monitors - Beta-emitters (Maximum Beta Energy Greater than 0.15 MeV) and Alpha-emitters

8963 Dosimetry of X and γ Reference Radiations for Radiation Protection Over the Energy Range 8 kev to 1.3 MeV

IEC Standards

IEC standards are international standards issued by the International Electrotechnical Commission. They are available from ANSI.

325 Alpha, Beta, and Alpha-beta Contamination Meters and Monitors

395 Portable X or Gamma Radiation Exposure Rate Meters and Monitors for Use in Radiologic Protection

405 Nuclear Instruments: Construction Requirements to Afford Personal Protection Against Ionizing Radiation

407 Radiation Protection in Medical X-ray Equipment 10 kV to 40 kV

463 Low Energy X or Gamma Radiation Portable Exposure Rate Meters and Monitors for Use in Radiological Protection

846 Beta, X, and gamma Radiation Dose Equivalent and Dose Equivalent Rate Meters for Use In Radiation Protection

Federal Sector Laboratory Accreditation Criteria

This describes the criteria that Federally owned secondary-level laboratories calibrating ionizing radiation instruments or irradiating dosimeters must meet to be accredited by NVLAP. It is anticipated that eventually criteria will be developed for testing laboratories as well as calibration laboratories. The criteria document and information on this program is available from:

National Institute of Standards and Technology
National Voluntary Laboratory Accreditation Program
Att. Robert Gladhill
Gaithersburg, MD 20899

BSC Documents

The documents describe the requirements on calibration laboratories in the United Kingdom to provide a comprehensive service for the calibration of instruments against recognized standards. For more information on these standards contact:

British Calibration Service
National Physical Laboratory
Teddington
Middessex TW110LW
England

For a comparable set of criteria for Federally owned secondary-level laboratories in the United States, see Federal Sector Laboratory Accreditation Criteria

0021 The British Calibration Service

0802 General Criteria for Laboratory Approval Calibration of Radiological Instruments

0803 General Criteria for Laboratory Approval Provision of Personal Dosimetry Services

0811 Supplementary Criteria for Laboratory Approval Calibration of Radiological Protection Level Instruments: X-, Gamma-, and Beta-rays

0813 Supplementary Criteria for Laboratory Approval Calibration of Radiological Protection Level Instruments: Neutrons

0821 Supplementary Criteria for Laboratory Approval Calibration of Personal Dosimetry Services Using Film Dosimeters for Beta, Gamma, X-, and Thermal Neutron Radiations

0822 Supplementary Criteria for Laboratory Approval Calibration of Personal Dosimetry Services Using Nuclear Emulsion Film Dosimeters for Neutron Radiations

0823 Supplementary Criteria for Laboratory Approval Calibration of Personal Dosimetry Services Using Thermoluminescent Dosimeters for Beta, Gamma, X-, and Neutron Radiations

6601 Calibration of Radiological Instruments at Protection and Therapy Levels

NRPB Reports

The reports listed here are examples of the instrument type test reports issued by the National Radiological Protection Board in the UK. This is not a complete list of these reports. For more information on these reports contact:

Publication Officer
National Radiological Protection Board
Harwell
Didcot
Oxfordshire, England

IE2 White, D. F., K. Callowhill W. J. Iles and D. L Speight, Instrument Evaluation No. 2 Eberline Portable Ion Chamber Model RO-1

IE3 White, D. F., K. Callowhill W. J. Iles and D. L Speight, Instrument Evaluation No. 3 Eberline Portable Ion Chamber Model RO-2

IE6 Iles, W. J., D. R. Blundell, K. Callowhill and D. F. Whitem, Instrument Evaluation No. 6 Victoreen 440 RF Shielded Low-energy X-ray Survey Meter

IE12 Burgess, P. H. and W. J. Iles, Instrument Evaluation No. 12 Victoreen Panoramic 470A Survey Meter

IE15 Burgess, P. H. and W. J. Iles, Instrument Evaluation No. 15 A Summary of the Performance of Exposure Rate and Dose Rate Instruments Contained in Instrument Reports NRPB-IE1 to NRPB-IE13

IE22 Burgess, P. H. and W. J. Iles, Instrument Evaluation No. 22 Dosimeter Corporation of America Portable Survey Meter Type 3795 "True Blue"

IE27 Burgess, P. H., Instrument Evaluation No. 27 Victoreen 471 RF Radiation Survey Meter

IE28 Burgess, P. H., Instrument Evaluation No. 28 Keithley Model 36100 Survey Meter

IE29 Burgess, P. H., Instrument Evaluation No. 29 Nuclear Enterprises PDR2 Dose Rate Meter

Journals

Applied Radiation and Isotopes

IEEE Transactions on Nuclear Science and Applications

Journal of Radiological Protection

Health Physics

Medical Physics

Nuclear Instruments and Methods in Physics Research

Physics in Medicine and Biology

Radiation and Environmental Biophysics

Radiation Physics and Chemistry

Radiation Protection Dosimetry

Radiation Research

Review of Scientific Instruments

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APPENDIX B

CRITERIA FOR THE OPERATION OF FEDERALLY-OWNED CALIBRATION LABORATORIES (IONIZING RADIATION)

This appendix includes the latest draft of the accreditation criteria for federally-owned calibration laboratories. The primary purpose of including it in this report is to provide guidance on the requirements a laboratory must satisfy if it wants to become a secondary-level laboratory for calibrating instruments. While no tertiary-level criteria presently exists, it is anticipated that it will be similar to the criteria for the secondary-level laboratories but less rigorous. Once the system identified in the criteria is fully operational, it is anticipated that the criteria will be expanded to include other categories such as testing laboratories.

The latest copy of the criteria is available from:

National Institute of Standards and Technology
National Voluntary Laboratory Accreditation Program
Att. Robert Gladhill
Gaithersburg, MD 20899

CRITERIA FOR THE OPERATION

OF

FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

(IONIZING RADIATION)

November 1989

TABLE OF CONTENTS

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART A - GENERAL CRITERIA

1. INTRODUCTION

This document contains the criteria for accreditation of federally-owned laboratories that calibrate ionizing radiation instrumentation (as defined in the glossary). Adherence to these criteria will assure that the laboratory is capable of high standards of performance in the calibration of instrumentation for use in various radiation environments.

The criteria contained in Part A of this document shall be satisfied by all laboratories seeking accreditation. In addition, each laboratory shall satisfy the specific criteria contained in other parts of this document for each category (radiation type and energy) for which accreditation is desired.

2. LABORATORY MANAGEMENT AND STAFF

2.1 Management

The manager of the laboratory shall have a position in the organizational structure which assures the authority to conduct laboratory operations free from any influence that could adversely affect the quality or impartiality of the services offered. This individual shall have a minimum of a bachelor's degree in physics, engineering, health physics, or radiological physics, and should have a graduate degree in one of these or a closely related scientific field. This individual shall understand the laboratory protocol, be responsible for assuring that it is being followed, and shall at least annually evaluate staff competence and the need for training.

The laboratory manager shall be responsible for verification at least annually that documented procedures are properly being followed and check the correctness of calibration of individual instruments. A complete record of such checks shall be maintained and available for audit.

The individual in charge of day-to-day operation of the laboratory shall have at least three years of practical experience in radiation measurement, including the calibration of radiation instrumentation.

2.2 Operating Staff

The staff employed in calibration work shall have appropriate training or experience, be adequately supervised and follow documented procedures. Each such individual shall understand that responsibility for the correctness of a calibration lies with the individual performing it.

3. PHYSICAL ASPECTS OF THE LABORATORY

3.1 Location

The effect of external conditions on the internal environment of the laboratory shall be considered in selection of the laboratory site. The laboratory should be sited away from, or otherwise isolated from, sources of mechanical vibration and shock, sources of electrical and electromagnetic interference, and other potential sources of interference with the proper calibration of instrumentation. If such potential sources exist, the laboratory shall have documentation that demonstrates no adverse effects on calibration accuracy.

3.2 Environment

Environmental monitoring equipment shall be provided for indicating the temperature, atmospheric pressure, and humidity within the laboratory at all times.

In general, strict temperature control is not essential for the calibration work covered by these criteria. It is, however, desirable that the laboratory be kept at reasonably uniform temperature so that the accuracy of calibration is not adversely affected and to ensure that an adequate level of stability is reached before the start of calibration measurements. The laboratory temperature should be maintained within the range of 20 to 24 degrees centigrade. When using a vented ionization chamber, the temperature shall not vary more than ± 2°C in any one hour during which a calibration is conducted.

The relative humidity should be within the range of 15 to 65 percent for routine laboratory operation.

The level of background radiation shall be maintained as low as practicable and not subject to variations that could significantly affect the accuracy of calibration work. Radiation sources not used for calibration should not be stored in the radiation room.

3.3 Services

The electrical power shall be appropriate to the equipment used, suitably stable, and free of switching surges and significant line noise. When necessary, local auxiliary voltage stabilizers and filters shall be provided.

The laboratory shall be provided with an adequate grounding system. Where there is a likelihood of interference arising from equipment connected to a single grounding system, separate grounding systems shall be provided and adequate precautions taken against any possible interconnection between systems.

If compressed air is used, a pressure regulator and means for removing moisture, dust, and oil from the compressed air should be provided.

4. CALIBRATION FACILITIES AND EQUIPMENT

4.1 Facilities

The laboratory shall have free-air conditions for all radiation beams used for calibrations.

The radiation room (or rooms) shall be of sufficient size and design that scattered radiation at the position where instrumentation is normally placed for calibration does not introduce an error inconsistent with overall accuracy goals. If necessary, proper scatter corrections shall be applied.

4.2 Equipment

The equipment available in the laboratory shall be appropriate to the calibration services offered and the procedures employed in the calibrations. Specific requirements for each service provided are given in appropriate parts of this document.

No new equipment shall be put into service until it has been properly checked and, where appropriate, calibrated.

The laboratory shall have secondary radiation measurement standards that cover the range of calibrations performed. The secondary standards should be used only for calibration of instruments and not for any other purpose. A working standard should be used in lieu of a secondary standard for routine reference.

The laboratory shall have a barometer capable of one percent accuracy and a thermometer capable of ± 1°C accuracy. Each shall have been calibrated by comparison with a tertiary or higher-level standard. A calibrated hygrometer capable of monitoring relative humidity with an accuracy of five percent relative humidity shall be available.

The laboratory shall have an instrument and radiation source positioning system. The support shall be rigid and enable the reproduction of a desired source/detector geometry. It shall produce minimum scattered radiation.

All equipment used in the laboratory that was calibrated prior to the initial accreditation of the laboratory, and all subsequent replacements for those items of equipment, shall be subject to a documented program for quality control, and shall be recalibrated as necessary.

5. OPERATIONAL PROCEDURES

5.1 Laboratory Protocol

The laboratory shall have a written protocol. Each page of the protocol shall indicate the date of inception or revision. The protocol shall include the following:

1. A statement of the scope of the laboratory's work, including all of the radiation types, energies, and intensities for which calibrations are provided.

2. A statement of policy regarding acceptance of instrumentation for calibration. Examples are policy regarding instruments that are contaminated, in need of repair, or of a particular type not accepted. Restrictions on type of customer or liability for instrument damage should also be stated.

3. A statement of the laboratory's accuracy goals for the calibrations it performs. These accuracies shall be in terms of deviations from a national standard.

4. A method of documenting the model and serial number of each critical piece of equipment that is used in any calibration.

5. The procedure for calibrating each piece of laboratory support equipment and a statement of the conditions under which recalibration is to be performed.

6. A fully documented procedure for each type of instrumentation calibrated. The procedure shall provide the appropriate operational steps to permit a knowledgeable person to reproduce a particular calibration technique with a precision consistent with the accuracy goals of the laboratory. Each calibration procedure shall give the following information, as a minimum:

a. A concise but complete account of the procedure.

b. The scope and limitations of the procedure.

c. Any environmental constraints that must be met in calibrating the instrumentation, in addition to those stated in 3.2.

d. The sequence of the calibration procedure, drawing attention to special precautions.

e. The equipment and standards to be used in this calibration procedure.

f. An example of a completed data sheet (or computer record) for the calibrated instrumentation.

g. The method of data handling and reduction.

7. An assessment of the uncertainty associated with each calibration procedure. The total systematic and total random uncertainties shall be determined separately by combining the individual systematic or random uncertainties in quadrature. The total uncertainty shall be determined by combining the total systematic and total random uncertainties, and the method used for that combination shall be stated.

8. An example of a completed calibration report, including a statement of the accuracy to which the reference value of the radiation field is known.

9. The procedure or reference for auditing calibration data and approving reports.

10. The procedure to ensure the security of calibration records.

5.2 Amendments to Procedures and Protocol

Any new or amended calibration procedure that could have a significant effect on the accuracy of a calibration shall be approved by the accrediting body before it is adopted for routine use. A copy of the latest revision of the laboratory's protocol shall be available for audit at all times.

5.3 Notification of Mistakes

If the laboratory discovers a mistake in a calibration report that significantly affects the accuracy of the calibration, the person or institution that received the report shall be notified within 24 hours, if possible, and a written report of the mistake sent to that person or institution within 72 hours. The mistake shall be corrected as soon as possible by sending a corrected calibration report or recalibrating the instrumentation. The laboratory shall determine the reason for the mistake and take corrective action to prevent its reoccurrence.

If the laboratory discovers an apparent generic error in one of its procedures or in the design of an item of instrumentation that has or could lead to an erroneous calibration, it shall notify the accrediting body in writing within 10 days. Other accredited laboratories may then be notified of the problem, along with recommendations for remedial action.

5. ACCURACY AND QUALITY ASSURANCE

6.1 Calibration of Laboratory Standards

The standards or equipment originally calibrated by comparison with a higher-level standard shall be recalibrated when the need is demonstrated by the results of proficiency testing or routine quality control.

6.2 Accuracy of Services

The laboratory shall be capable of providing calibration services with accuracies as indicated in the appropriate parts of this document. Each accuracy shall be stated in terms of percent deviation from the national standard.

6.3 Quality Control

The laboratory's procedures shall be designed and operations conducted to discover undesired changes in the performance of equipment on which the quality of a calibration depends. Such quality control procedures, and the frequency of their use, shall be specified in the laboratory's protocol.

The laboratory's proficiency shall be tested annually by the National Institute of Standards and Technology (NIST) for those types of calibrations provided by the laboratory. Each proficiency test shall be representative of one or more types of calibration for which the laboratory is accredited. If the test results indicate that corrective action is required, the laboratory shall take action to achieve the accuracy stated in the appropriate part of this document.

7. RECORDS AND REPORTS

7.1 Record System

A comprehensive and readily available record system shall be maintained by the laboratory and shall include at least the following:

1. A full history and calibration data, including certificates, for all standards and applicable calibration equipment.

2. An inventory of all standards and calibration equipment.

3. All procedures used for providing calibration services.

4. A bound day-book, or other equivalent record, in which is recorded a description, sufficient for identification, of every item of instrumentation for which a calibration service was provided and the date that the calibration was performed. The day-book or other record shall also include or reference a detailed report for that specific calibration.

5. Information essential to the analysis and reconstruction of the calibration of a specific item of instrumentation.

6. A record of routine quality control actions and any resultant control charts.

7. Copies of all calibration reports issued.

8. The results of all proficiency testing.

9. Records detailing the education, experience, and training of all operating staff and supervisory personnel.

All records of data shall identify the individual who collected the data on which the record is based. Records for all individual items of instrumentation calibrated shall be maintained for a period of at least five years. Records regarding calibration of standards used shall be maintained for a period of at least 50 years.

If calibration data are stored in a computer, the laboratory protocol shall specify how backup is provided (i.e., data protection procedures).

7.2 Calibration Reports

A calibration report shall be issued for each item of instrumentation calibrated under the scope of accreditation, including an appropriate statement clearly specifying the conditions (e.g., orientation of the detector) under which the calibration was performed. It should also state limitations to the calibration, i.e., maximum range calibrated if less than the indicated range of an instrument, scales not calibrated, application of correction factors, etc.

The uncertainty associated with the calibration shall be stated.

The report form shall include the following statement and the appropriate box shall be checked:

"This calibration ☐ was ☐ was not performed using a procedure which is within the scope of accreditation."

Alternatively, the statement shall be made by choosing either "was" or "was not" as appropriate, without showing the other possible choice.

Calibration reports shall be signed by the laboratory manager or designated alternate.

CRITERIA FOR THE OPERATION OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART B.1 - GAMMA-RAY CALIBRATION OF SURVEY INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of health physics instruments at radiation protection levels using one or more gamma-ray sources. These criteria are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if this gamma-ray calibration service is offered and its inclusion in the Scope of Accreditation is desired.

2. SOURCES OF GAMMA RADIATION

One or more of the following radiation sources shall be available for use in the calibration of health physics instruments:

Radionuclide	Nominal Energy
^{241}Am	60 keV
^{137}Cs	660 keV
^{60}Co	1.25 MeV

The radiation fields produced by the sources shall cover a range of exposure rates suitable for protection-level calibration. A minimal range is 1 mR/h to 5 R/h; and, a more desirable range is 0.5 mR/h to at least 100 R/h.

3. RADIATION CONTROL

3.1 Shielding

Radiation barriers and/or storage containers for sources shall provide sufficient shielding so that radiation added to natural background radiation in the calibration area is sufficiently low as to not interfere with ongoing calibration work. Added background radiation and leakage radiation from all sources in the calibration area should not contribute more than one percent of the total exposure rate at which an instrument is calibrated.

3.2 Beam Collimation

The gamma radiation beam emitted from a source that has been exposed for calibration shall be collimated so that its size is limited to an area consistent with calibration requirements. An exception to this requirement is calibration facilities sufficiently large to provide a low scatter radiation environment for instrument calibration, e.g., an uncollimated source in a low scatter room.

3.3 Source Exposure

The source storage container shall have a mechanism to control exposure in the gamma beam. If the radiation source is used for calibration of exposure measuring (as contrasted with exposure-rate measuring) instruments, the shutter or source transit time and its effect on the total radiation exposure shall be known.

3.4 Exposure Control

If the radiation source is used for the calibration of exposure measuring instruments (see 3.3, above), the shutter or source transfer shall be initiated and terminated by a timer or the exposure shall be controlled by use of a transmission chamber. Any associated systematic timing uncertainties shall be documented and eliminated or compensated.

4. EQUIPMENT

In addition to one or more radiation sources and associated control devices, the laboratory shall have as a minimum the following equipment:

a. Secondary standard ionization chambers suitable for the photon energy and intensity ranges for which calibration services are offered.

b. An electrometer to measure the charge produced in the ionization chambers.

c. A voltage source suitable for chamber polarizing potential.

d. An independent measuring system for verification of the performance of the secondary standard ionization chambers and electrometer.

e. An instrument and ionization chamber support and positioning system. The system should provide for reproducible and accurate positioning of an instrument or chamber with respect to the radiation source. For beam type irradiation configurations, the positioning system should define the central axis of the gamma beam.

Additional equipment should include a pulse generator, oscilloscope, current source, precision capacitors and precision resistors.

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Exposure Rate

The gamma radiation field used for calibration shall be characterized in terms of exposure rate at a given position or distance from the source. The exposure rate shall be known at each distance used.

5.2 Scattered Radiation

The effect of scattered radiation (relative to a radiation field with minimal scatter) on the accuracy of calibration of each instrument type shall be known at each location where a detector is placed for instrument calibration. The approximate energy spectrum of the scattered radiation field should be known.

5.3 Attenuation

If an attenuator is used to reduce the exposure rate at any location in the radiation field, the effect of the altered radiation spectrum (relative to an unattenuated radiation spectrum) on the accuracy of calibration of each instrument type shall be known. The approximate energy spectrum of the attenuated radiation field should be known. Secondary electron equilibrium at the calibration position shall be documented.

5.4 Accuracy

The exposure rate specified by the laboratory as its reference value for each source of radiation shall be within five percent of the true value as defined by comparison with a national standard above 10 mR/h, and within seven percent of the true value from 0.5 mR/h to 10 mR/h. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the radionuclide or photon energy used, the reference exposure rate or rates at which the instrument was calibrated, the exposure rate indicated by the instrument, and the correction factor at each calibration point. In the case of integrating instruments, in addition to the radionuclide and exposure rate, the reference exposure, instrument reading, and correction factor shall be included. At least one calibration point should be included for each range of the instrument, where applicable. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report, and the use of a build-up cap shall be noted. For instruments that use a vented ionization chamber, the reported values shall be referenced to a temperature of 22°C and a barometric pressure of 760 mm Hg, and the equation needed to convert to other temperatures and pressures shall be provided.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART B.2 — X-RAY CALIBRATION OF SURVEY INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of health physics instruments at radiation protection levels using an x-ray source. These criteria are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if this x-ray calibration service is offered and its inclusion in the Scope of Accreditation is desired.

Criteria for calibration of instruments for diagnostic levels using an x-ray source are contained in Part E.1.

2. SOURCE OF X RAYS

A constant potential x-ray generator shall be available for use in the calibration of health physics instruments. Its maximum ripple shall not exceed two percent and it should be operable over a minimum range of 30 to 150 kV, 1 to 10 mA.

3. CONTROL OF THE RADIATION BEAM

3.1 Radiation Production

The production of a useful beam of radiation may be by means of the application of high voltage to the x-ray tube or the opening of a mechanical shutter (which normally acts as a shield to the x-ray beam).

3.2 Beam Collimation

The x-ray beam emitted from the tube housing shall be collimated so that its size is limited to an area consistent with calibration requirements. Provisions shall be made for identifying the central axis and boundaries of the useful area of the beam.

3.3 Exposure Control

If the radiation source is used for the calibration of exposure measuring instruments, the radiation beam shall be controlled by a timer or the exposure shall be controlled by use of a transmission chamber. The timing error due to the shutter transit times or high voltage ramping shall be known.

4. EQUIPMENT

In addition to one or more x-ray machines and associated control devices, the laboratory shall have the same minimum equipment as that required for gamma ray calibration (see Part B.1, Section 4) with the following exception - the secondary standard ionization chambers shall be appropriate to the energy and intensity of x rays for which calibration services are offered.

Additionally, the laboratory shall be equipped with filters to permit the production of a variety of x-ray beam qualities (see paragraph 5.3, below).

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Exposure Rate

The x-ray radiation field used for calibration shall be characterized in terms of exposure rate at a given position or distance from the anode of the x-ray tube. The exposure rate shall be known at each distance used. During calibration of an instrument, the exposure rate shall not vary by more than two percent from the nominal rate.

5.2 Scattered Radiation

The contribution to the exposure rate from scattered radiation shall not exceed five percent at any location where a detector is placed for instrument calibration.

5.3 Radiation Quality

The x-ray beam emitted from the tube housing shall be filtered before use to provide the appropriate radiation quality for calibration purposes. If a transmission chamber is used for routine beam monitoring, it shall be considered to be added filter material. Three or more of the beams shown in Table 1 shall be available.

The first half-value layer and homogeneity coefficients for a given x-ray beam shall be within five percent, and seven percent, respectively, of the values shown in Table 1. If necessary the indicated tube voltage or added filter, or both, may be adjusted to achieve those values.

The intensity of the x-ray beam shall not vary more than five percent across the useful area of the beam.

The radiation quality shall be checked for stability at least annually. Whenever any part that could affect the beam quality is repaired or replaced the above requirements for radiation quality shall be met.

5.4 Accuracy

The exposure rate specified by the laboratory as its reference value for each x-ray beam shall be within five percent of the true value as defined by comparison with a national standard above 10 mR/h, and within seven percent of the true value from 0.5 mR/h to 10 mR/h. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the x-ray beam used for calibration, the reference exposure rate or rates at which the instrument was calibrated, the exposure rate indicated by the instrument, and correction factor at each calibration point. In the case of integrating instruments, in addition to the x-ray beam and exposure rate, the reference exposure, instrument reading, and correction factor shall be included. At least one calibration point should be included for each range of the instrument, where possible. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report. For instruments that use a vented ionization chamber, the reported values shall be referenced to a temperature of 22°C and a barometric pressure of 760 mm Hg, and the equation needed to convert to other temperatures and pressures shall be provided.

TABLE 1

		Critical characteristics[1]				Relevant information[2]							
Beam Code	Prev. Code	Half-Value Layer		Homogeneity Coefficient		Added Filter				Effective Energy	Distance	Exposure Rate	
		Al (mm)	Cu (mm)	Al	Cu	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	(keV)	(cm)	Min. (mR/s)	Max. (R/s)
L10	L-B	0.029		79		0.					25	0.001	1.7
L15	L-C	0.050		74		0.					25	0.001	4.2
L20	L-D	0.071		76		0.					50	0.001	3.3
L30		0.22		60		0.265					50	0.001	0.4
L40		0.49		57		0.50					50	0.001	0.4
L50		0.75		58		0.639					50	0.001	0.4
L80		1.83		58		1.284					50	0.001	0.4
L100	L-M	2.8		59		1.978					50	0.001	0.4
M20		0.152		79		0.230					50	0.001	0.5
M30	L-G	0.36		64		0.50					50	0.001	0.3
M40		0.73		66		0.786					50	0.001	0.4
M50	L-I	1.02	0.032	66	62	1.021					50	0.001	0.4
M60	MFB	1.68	0.052	68	64	1.51						0.8	0.2
M100	MFG	5.0	0.20	72	55	5.0						1.0	0.3
M150	MFI	10.2	0.67	87	62	5.0	0.25					1.0	0.4
M200		14.9	1.69	95	69	4.1	1.12					1.0	0.3
M250	MFO	18.5	3.2	98	86	5.0	3.2					1.0	0.2
M300		22.	5.3	100	97	4.0		6.5				0.5	0.03
H10		0.048		89		0.105					25	0.001	0.003
H15		0.152		87		0.500					25	0.001	0.003
H20		0.36		88		1.021					50	0.001	0.003
H30		1.23	0.038	93	94	4.13					50	0.001	0.003
H40		2.9	0.093	94	95	4.05	0.26				50	0.001	0.003
H50	HFC	4.2	0.142	92	90	4.0			0.10	38		0.3	0.005
H60		6.0	0.24	94	89	4.0	0.61			46		0.02	0.005
H100		13.5	1.14	100	94	4.0	5.2			80		0.005	0.002
H150	HFG	17.0	2.5	100	95	4.0	4.0	1.51		120		0.03	0.010
H200	HFI	19.8	4.1	100	99	4.0	0.60	4.16	0.77	166		0.02	0.006
H250	HFK	22	5.2	100	98	4.0	0.60	1.04	2.72	211		0.03	0.005
H300		23	6.2	99	98	4.1		3.0	5.0	252		0.04	0.003

(1) The half-value layer and homogeneity coefficient shown for a beam shall be matched by the laboratory within limits prescribed by pertinent parts of these criteria. In the beam code, the letter indicates light, moderate, heavy filtration, and the number is the constant potential in kilovolts.

(2) This information relates specifically to the NIST beams, and may provide useful guidance to a laboratory that is seeking accreditation. The inherent filtration of the NIST beams is approximately
1.0 mm Be for beam codes L10-L100, M20-M50, H10-H40, and
3.0 mm Be for beam codes M60-M300, H50-H300.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART B.3 — BETA-PARTICLE CALIBRATION OF SURVEY INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of health physics instruments at radiation protection levels using a beta particle source. These criteria are limited to the calibration of instruments used to measure dose rate from external beta sources and are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if this beta-particle calibration service is offered and its inclusion in the Scope of Accreditation is desired.

2. SOURCE OF BETA PARTICLES

The selection of a source for beta particle calibration of an instrument will depend both on the nature of the radiation field in which the instrument is to be used and the anticipated energy of the beta radiation. It is recommended that both point sources and distributed sources be available for instrument calibration since they represent the extremes of measurement geometry. The radionuclides listed in Table 2 are recommended for use as reference sources for beta calibration; however, other sources may be used if they more accurately represent the beta energy spectrum in which the calibrated instrument is to be used.

The laboratory shall have at least the following radionuclide sources of beta particles:

^{147}Pm, ^{204}Tl, and $^{90}Sr/Y$.

These sources shall comply with the ISO 6980 standard.

TABLE 2

Radionuclide	E_{max} (keV)	Half-Life (years)
^{147}Pm (a)	225	2.62
^{99}Tc	290	~ 2×10^5
^{85}Kr	670	10.8
^{36}Cl	710	~ 3×10^5
^{204}Tl	763	3.8
$^{90}Sr/Y$ (b)	2270	28.5
Natural U	2290	~ 4×10^9
Depleted U	2290	~ 4×10^9
$^{106}Ru/Rh$	3540	1.0

(a) ^{147}Pm usually also contains ^{146}Pm, which has an E_{max} = 780 keV.

(b) The source should be sealed with 100 mg/cm^2 (nominal) filtration to remove the ^{90}Sr beta component.

3. RADIATION BEAM CONTROL AND PARAMETERS

3.1 Radiation Production

The production of a beam (field) of beta radiation for instrument calibration may be achieved by means of a shutter exposing the source or by moving the source to an exposed position.

3.2 Beam Parameters

The physical size of the beta ray beam (field) shall have been predetermined to assure that it is sufficiently large to accommodate the instrument being calibrated. Provisions shall be made for identifying the central axis and boundaries of the useful area of the beam. If necessary, beam flattening filters may be used to meet the requirements of paragraph 5.4.

3.3 Timer

If the radiation source is used for the calibration of fluence measuring instruments, the radiation beam shall be controlled by a timer. The timing error due to the shutter transit times shall be known.

4. EQUIPMENT

In addition to an appropriate selection of beta ray sources, the laboratory shall have the same minimum equipment as that required for gamma ray calibration (see Part B.1, Section 4); however, in this case the secondary standard ionization chamber shall be a thin-window fixed volume ionization chamber or an extrapolation chamber. The extrapolation chamber or thin-window ionization chamber response shall have been verified by the NIST or by comparison to NIST or PTB calibrated beta radiation sources and have an accuracy equivalent to that described in paragraph 5.5, below, over the anticipated range of irradiation conditions, *i.e., beta energy and depth of dose measurement point.*

5. CHARACTERIZATION OF THE BETA RADIATION FIELD

5.1 Dose Rate

The beta radiation fields used for calibration shall be characterized in terms of absorbed dose rate (at a depth in tissue of 7 mg/cm^2) at a given position or distance from the source. The dose rate shall be known at each distance used. Similarly, if calibrations are to be done at other tissue depths (for example, at 300 mg/cm^2 to simulate exposure of the lens of the eye, rather than 7 mg/cm^2 for the skin), then the dose rate at these depths shall be known.

5.2 Attenuation

In order to assure that the energy of the beta radiation that reaches the detector is similar to that originating from the radionuclide, certain limits on the calibration conditions are recommended. If E_{res} refers to the residual maximum energy of a beta particle reaching the detector of an instrument and E_{max} is the energy at which the beta particle originates, then the conditions shown in Table 3 should be met.

TABLE 3

E_{max}	E_{res}/E_{max}
<100 keV	0.6
100 - 800 keV	0.7
>800 keV	0.8

These conditions are recommended so that no undue attenuation from the source's self-absorption, containment, beam flattening filters, or air attenuation will significantly change the radionuclide's beta spectrum. The procedure for determining E_{res} is given in the ISO 6980 standard.

5.3 Contamination

In addition to the radiation quality considerations on which the preceding paragraphs impact, source contamination by other radionuclides may significantly change the beta or gamma radiation field from a source. Small levels of beta contamination are difficult to detect but fortunately are usually accompanied by gamma contamination. The beta spectral purity is considered adequate if the following hold:

1. The plot used to measure R_{res} has a linear section, and;

2. The E_{res} value meets the criteria in Table 3.

For requirement 1 above, R_{res} is the range in an absorbing material of a beta spectrum of residual maximum energy, E_{res}. The procedure for measurement of R_{res} is given in the ISO 6980 standard.

Measurement to determine the adequacy of beta spectral purity shall be made every two years, or more often if needed.

Photon contamination of the beta field due to sources of gamma, x-ray, and bremsstrahlung radiation should contribute less than five percent of the total absorbed dose.

5.4 Uniformity of Beta Field

The beta dose rate should be uniform over the area of the detector face. The dose rate across the beam profile at a depth of 7 mg/cm^2 should not vary more that five percent from the mean dose rate for E_{res} greater than or equal to 300 keV, and not more than ten percent for E_{res} less than 300 keV. The uniformity of the beta field shall be verified by measurement with a small area detector or film.

5.5 Accuracy

The dose rate specified by the laboratory as its reference value for each beta-particle beam shall be within ten percent of the true value as defined by comparison with a national standard. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the radionuclide and radiation field type (point source or flat field) used for calibration, the reference dose rate or rates at which the instrument was calibrated, and the dose rate (or dose) indicated by the instrument at each calibration point. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report. The report should state whether the front face or the effective center of the detector was located at the point where the reference field was characterized.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART B.4 - NEUTRON CALIBRATION OF SURVEY INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of health physics instruments at radiation protection levels using neutron radiation. These criteria are supplementary to the general criteria contained in part A. Both the general criteria and these specific criteria shall be followed if this neutron radiation calibration service is offered and its inclusion in the Scope of Accreditation is desired.

2. SOURCE OF NEUTRON RADIATION

The selection of a source for neutron radiation calibration of an instrument will depend both on the nature of the radiation field in which the instrument is to be used and the anticipated energy spectrum of the neutron radiation. The neutron sources described in Table 4 are frequently used for instrument calibration.

As a minimum, a laboratory shall have at least one of the sources shown in Table 4 with appropriate strength for the dose equivalent or dose equivalent-rate range of the instruments to be calibrated. A minimum dose equivalent rate range is 10 mrem/h to 1 rem/h. The neutron source strength shall be certified by or traceable to the NIST. If a ^{252}Cf source is used, the laboratory shall be capable of calibrating an instrument using both the bare source and the moderated configuration.

TABLE 4

Characteristics of Commonly Used Fast Neutron Sources
For Calibration of Neutron Survey Instruments (Lorenz, 1972)

Source	Method of Neutron Production	Half-life	Neutron Energy (MeV) Max.	Average
^{238}Pu (Be)	(α,n)	86.4 Y	11.3	5.0
^{239}Pu (Be)	(α,n)	24390 Y	10.74	4.5-5
^{241}Am (Be)	(α,n)	458 Y	11.5	5.0
^{252}Cf	SF	2.654 Y	15	2
^{252}Cf Moderated with 15 cm D_2O (e.g., Schwartz, 1980; Prevo, 1983)	SF	2.654 Y	15	0.54

The radiation field produced by a neutron source used for calibration shall provide an energy spectrum and dose equivalent rates appropriate for the instrument undergoing calibration.

3. RADIATION CONTROL AND PARAMETERS

3.1 Radiation Production

The production of a field of neutron radiation for instrument calibration should be achieved by moving the source from a shielded to an exposed position, preferably in a low-scatter environment in an open area or at the center of a large room (for example, 10×10 meters square with the source 4 meters from both floor and ceiling). The neutron radiation field shall be carefully monitored and controlled. The response due to scattered neutrons at the point of calibration should be less than 25 percent of the total instrument response, and the appropriate corrections shall be made.

3.2 Timer

If the neutron source is used for the calibration of integrated dose equivalent measuring instruments, the radiation field shall be controlled by a timer. Any associated systematic timing uncertainties shall be documented and eliminated or compensated.

4. EQUIPMENT

In addition to a selection of one or more neutron sources appropriate to the radiation field(s) for which instruments are being calibrated, the laboratory shall have the same minimum equipment as that required for gamma-ray calibration (see Part B.1, Section 4), with the exception of secondary standard ionization chambers and that equipment associated with their use. An instrument of each type calibrated should be available for the measurement of the contribution of scattered radiation to the total instrument response.

5. CHARACTERIZATION OF THE NEUTRON RADIATION FIELD

5.1 Dose Equivalent Rate

The neutron radiation field used for calibration shall be characterized in terms of the flux density (fluence rate) and spectral composition at the point of calibration. The dose equivalent rate shall be calculated on the basis of these characteristics (see Table 5) as a means of setting calibration points for specific instrument types.

TABLE 5

Characterization of neutron sources in terms of dose equivalent

Radionuclide source	Mean neutron fluence to dose equivalent Conversion factor[a]	Specific source Strength	Specific neutron dose equivalent rate at 1 m[b]
	$rem \cdot cm^2$	$s^{-1} \cdot Ci^{-1}$	$mrem \cdot h^{-1} \cdot Ci^{-1}$
^{238}Pu(Be)		2.0×10^6	
^{239}Pu(Be)		1.5×10^6	
^{241}Am(Be)	3.8×10^{-8}	2.4×10^6	2.7
		$s^{-1} \cdot mg^{-1}$	$mrem \cdot h^{-1} \cdot mg^{-1}$
^{252}Cf	3.4×10^{-8}	2.4×10^9	2.3×10^3
^{252}Cf moderated	9.1×10^{-9}	2.1×10^9	5.4×10^2

[a] The conversion factors were calculated from $\frac{1}{B} \int_0^\infty B_E \, h_\phi(E) dE$, where B is the neutron source strength, B_E is the spectral distribution of neutron source strength, and h_ϕ is the neutron fluence to dose equivalent conversion factor, i.e., the quotient of the dose equivalent and the neutron fluence, $\frac{H}{\phi}$. (Reference: ISO/DIS 8529.)

[b] These are typical numbers. Dose equivalent rate from a particular source depends upon variable factors such as purity, internal absorption, construction details, and encapsulation.

5.2 Radiation Quality

In addition to the radiation quality considerations on which the preceding paragraphs impact, contamination of the neutron field by other types of radiation may contribute to instrument response. If this is the case and the instrument is sensitive to photon and/or beta radiation as well as neutrons, the extent of this contamination shall be known and corrected for when calibrating a given instrument. Photon contamination of the neutron field shall be known and should be less than 20 percent of the total dose equivalent rate.

5.3 Accuracy

The dose equivalent rate specified by the laboratory as its reference value for each neutron field shall be within 10 percent of the true value as defined by comparison with a national standard. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the radionuclide and radiation field type (moderated or unmoderated) used for calibration, the free-field dose equivalent rate or rates at which the instrument was calibrated, the scatter-corrected instrument reading at each calibration point, and the basis for any calculation of dose equivalent rate from source emission rate. At least one calibration point should be included for each decade range of the instrument, where possible. The orientation of the instrument with respect to the radiation field shall be described or illustrated in the calibration report. The value of the scatter correction shall be provided.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART B.5 - ALPHA-PARTICLE CALIBRATION OF SURVEY INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of survey instruments at radiation protection levels using alpha radiation sources. These criteria are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if this alpha-particle calibration service is offered and its inclusion in the Scope of Accreditation is desired.

2. SOURCE OF ALPHA RADIATION

Planar or pseudo planar alpha radiation sources shall be used for the purpose of calibrating instruments used for the detection of alpha contamination. A pseudo planar source is one made up of a closely spaced array of small sources. The combined thickness of the source media and overburden shall be less than one-tenth the range of the least energetic alpha particle in these media. Only the following thin sources of alpha radiation are acceptable provided their two pi alpha emission rate (per unit area) is known and traceable to a source calibrated by the National Institute of Standards and Technology.

1. Natural or depleted uranium.
2. Plutonium-238 or -239.
3. Natural thorium or thorium-230.

The radiation fields produced by the sources shall cover a range of at least three decades of alpha emission rates suitable for protection-level calibration. A recommended range is 100 alpha particles per minute (two pi emission rate) to 10^6 alpha particles per minute.

3. RADIATION CONTROL

3.1 Source Exposure

Because of the short range of alpha particles in air, calibration measurements using an alpha source shall be made in such a way that the alpha radiation emitted from the source reaches the sensitive volume of the radiation detector. To assure that this is the case, there should be no shielding materials between the alpha source and the detector, other than that inherent to the detector or source itself. Additionally, the surface of the radiation detector should be no further than 3 millimeters from the surface of the alpha radiation source.

4. EQUIPMENT

In addition to radiation sources, the laboratory shall have as a minimum the following equipment:

(1) A source and detector support and positioning system. The system shall provide for reproducible and accurate positioning of a detector with respect to the radiation source.

(2) An independent measuring system used as a means of checking the sources for any degradation of their alpha emission rate.

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Emission Rate

The source used for calibration shall be characterized in terms of the alpha emission rate per unit area. The boundary of the source shall be greater than that of the detector. The relative standard deviation of the emission rate averaged over every individual segment of the source shall be less than ± 6 percent. The maximum area of a segment shall be 10 cm^2, and a segment shall not exceed 10 percent of the total surface area of the source. The spacing of smaller sources to form a pseudo array shall be such that the point-to-point distance between sources is less than the range of alpha radiation in air.

5.2 Accuracy

The alpha emission rate specified by the laboratory as its reference value for each source of radiation shall be within ten percent of the true value as defined by comparison with an appropriate standard traceable to the NIST. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the alpha radiation source used for calibration, the emission rate or rates at which the instrument was calibrated, and the instrument response at each calibration point. At least one calibration point and a linearity check should be included for each range of the instrument, where applicable.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART C.1 - GAMMA-RAY IRRADIATION OF PERSONNEL DOSIMETERS

1. INTRODUCTION

The criteria contained in this part of the document apply to irradiation of dosimeters at radiation protection and accident levels (as defined in ANSI N13.11) using gamma-ray sources. These criteria are supplementary to the general criteria contained in part A, and shall be followed if this specific irradiation service is offered and its inclusion in the Scope of Accreditation is desired. In that case, both the general criteria and these specific criteria shall be followed.

2. SCOPE

These criteria apply to irradiation of dosimeters used for personnel monitoring. They do not apply to dosimeters used for high-level (megarad) dosimetry in applications such as radiation processing or sterilization.

3. SOURCE OF GAMMA RADIATION

One or more ^{137}Cs source(s) of gamma rays shall be available for irradiation services. The radiation fields produced by the sources shall cover a range of exposures suitable for protection-level irradiations. The range covered will be a function of the mission and requirements of the laboratory but 30 mR to 500 R will suffice for most radiation protection purposes.

4. CONTROL OF RADIATION BEAM

4.1 Shielding

Source storage containers shall provide sufficient shielding such that leakage radiation does not interfere with other uses of the radiation room by raising the background level. Background radiation and leakage radiation from all sources in the radiation room shall not contribute more than 0.1% of the total exposure to which dosimeters are irradiated.

4.2 Beam Size and Uniformity

The gamma beam emitted from the irradiator should be collimated so that its size is limited to the minimum area consistent with irradiation requirements. All dosimeters shall be irradiated with phantom backing, and the beam size shall be sufficient to irradiate the entire phantom surface that is facing the source. If several dosimeters are irradiated simultaneously, the beam shall be sufficiently uniform and characterized to satisfy the requirements of section 6.3.

4.3 Beam Emission Control

The irradiator shall have a built-in device to control emission of the gamma beam. It shall be possible to operate the emission control device with a timer. Any associated random timing uncertainties due to transit time of the device shall be known. Any associated systematic timing uncertainties shall be measured and eliminated or compensated.

5. EQUIPMENT

In addition to radiation source(s) and the associated beam control devices, the laboratory shall have the same minimum equipment as that required for gamma-ray calibration (see Part B.1, Section 4), plus the following:

(1) Secondary standard ionization chambers that are calibrated for ^{137}Cs gamma rays and that cover the exposure rate ranges used for irradiation services.

(2) A phantom consisting of a slab of polymethylmethacrylate with a minimum cross section of 30 cm by 30 cm and a thickness of 15 cm. The support system for the phantom shall be rigid and produce minimum scattered radiation at the dosimeter position(s).

6. CHARACTERIZATION OF THE RADIATION FIELD

6.1 Exposure Rate

The gamma radiation field used for irradiation shall be characterized in terms of exposure rate in the absence of a phantom at the location where the center of the front surface of the phantom is placed for irradiation.

6.2 Scatter

The contribution from scattered radiation shall be determined with the phantom removed from the beam and shall not exceed 5% of the exposure rate at any location where a dosimeter is placed for irradiation. The approximate energy spectrum of scattered radiation shall be known.

The relationship between shallow dose and deep dose shall be measured for each facility because the charged particle surplus or deficit is highly dependent on local scattering conditions.

6.3 Accuracy

The exposure rate specified by the laboratory as its reference value shall be within 3% of the actual value defined by comparison with the national standard. This level of agreement with the national standard shall be periodically verified through proficiency tests of the laboratory by NIST. A description of the proficiency test is given in Appendix A. The total uncertainty of the dose delivered to an irradiated dosimeter shall be less than or equal to 5%. To meet this criterion, it may be necessary to use position-specific correction factors when several dosimeters are irradiated simultaneously.

7. IRRADIATION CONDITIONS

7.1 Orientation

The dosimeters shall be attached to one of the two larger surfaces of the phantom, at least 5 cm from any edge of the surface, and that surface shall face the radiation source. The central axis of the collimated beam shall be perpendicular to that surface, and shall pass through its geometric center. The position and orientation of the phantom shall be reproducible and verifiable.

7.2 Distance

The distance between the radiation source and the phantom surface to which the dosimeters are attached shall be one meter or more. The distance shall be reproducible and verifiable.

8. VERIFICATION OF TOTAL EXPOSURE

A method shall be used to verify the total exposure independent of the timer and known exposure rate.

9. IRRADIATION REPORT

The laboratory shall report to the customer the total exposure (in roentgens) for each dosimeter irradiated. For conversion to deep dose or dose equivalent, the value of the exposure shall be multiplied by 1.03 for ^{137}Cs.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART C.2 - X-RAY IRRADIATION OF PERSONNEL DOSIMETERS

1. INTRODUCTION

The criteria contained in this part of the document apply to the irradiation of dosimeters at radiation protection levels using x-ray beam sources. These criteria are supplementary to the general criteria contained in part A, and shall be followed if this specific i radiation service is offered and its inclusion in the Scope of Accredi' ation is desired. In that case, both the general criteria and these specific criteria shall be followed.

2. SCOPE

These criteria apply to the irradiation of dosimeters used for personnel monitoring.

3. SOURCE OF X-RAY IRRADIATION

At least one constant potential x-ray generator shall be available to cover a range of exposures for protection-level irradiations. The range covered will be a function of the mission and requirements of the laboratory but a minimal range is 30 mR to 500 R. The laboratory shall be able to perform irradiations using three or more of the filtered beams described in ANSI N13.11 and DOE/EH-0027 by NIST beam codes.

4. CONTROL OF RADIATION BEAM

4.1 Shielding

Leakage radiation through a closed shutter or x-ray tubehead shielding shall be less than 0.1% of the open-shutter rates at the position of the dosimeters.

4.2 Beam Size and Uniformity

The x-ray beams shall be collimated and their size should be limited to an area consistent with the irradiation requirements. All dosimeters shall be irradiated with phantom backing, and the beam size shall be sufficient to irradiate the entire phantom surface that is facing the tube head. If several dosimeters are being irradiated simultaneously, the beam size and beam uniformity shall be sufficiently uniform and characterized to satisfy the requirements of section 6.4.

4.3 Exposure Control

If a shutter is used to control the beam the shutter transit time shall be known.

If a shutter is not used radiation produced prior to achieving beam stability shall be known in all cases and shall be compensated. The uncertainties associated with stabilization shall be known. Any associated systematic timing uncertainties shall be documented and eliminated or compensated.

5. EQUIPMENT

In addition to one or more x-ray machines and the associated beam control devices, the laboratory shall have the same minimum equipment as that required for gamma-ray calibration (see Part B.1, Section 4), plus the following:

(1) A phantom consisting of a slab of polymethylmethacrylate with a minimum cross section of 30 cm by 30 cm and a thickness of 15 cm. The support system for the phantom shall be rigid and produce minimum scattered radiation at the dosimeter position(s).

(2) Secondary standard ionization chambers appropriate to the energy and intensity of x rays for which irradiation services are offered.

6. CHARACTERIZATION OF THE RADIATION FIELD

6.1 Exposure Rate

The radiation field shall be characterized in terms of exposure rate in the absence of a phantom at the location where the center of the front surface of the phantom is placed for irradiation.

6.2 Scatter

The contribution from scattered radiation shall be determined with the phantom removed from the beam and shall not exceed 5% of the exposure rate at any location where a dosimeter is placed for irradiation. The approximate energy spectrum of scattered radiation shall be known.

6.3 Radiation Quality

The first half-value layer and homogeneity coefficients for a given x-ray beam shall be within five percent and seven percent, respectively, of the values shown in Table 1. If necessary the indicated tube voltage or added filter, or both, may be adjusted to achieve those values. If a transmission chamber is used for routine beam monitoring, it shall be considered to be added filter material.

The intensity of the x-ray beam shall not vary more than five percent across the useful area of the beam.

The radiation quality shall be checked for stability at least annually. Whenever any part that could affect the beam quality is repaired or replaced the above requirements for radiation quality shall be met.

6.4 Accuracy

The exposure rate specified by the laboratory as its reference value shall be within 3% of the actual value defined by comparison with the national standard. This level of agreement with the national

standard shall be periodically verified through proficiency tests of the laboratory by NIST. A description of the proficiency test is given in Appendix A. The total uncertainty of the dose delivered to an irradiated dosimeter shall be less than or equal to 5%. To meet this criterion, it may be necessary to use position-specific correction factors when several dosimeters are irradiated simultaneously.

7. IRRADIATION CONDITIONS

7.1 Orientation

The dosimeters shall be attached to one of the two larger surfaces of the phantom, at least 5 cm from any edge of the surface, and that surface shall face the radiation source. The central axis of the collimated beam shall be perpendicular to the surface, and shall pass through its geometric center. The position and orientation of the phantom shall be reproducible and verifiable.

7.2 Distance

The distance between the radiation source and the phantom surface to which the dosimeters are attached shall be one meter or more. The distance shall be reproducible and verifiable.

8. VERIFICATION OF TOTAL EXPOSURE

A method shall be used to verify the total exposure independent of the timer and known exposure rate.

9. IRRADIATION REPORT

The laboratory shall report to the customer the total exposure (in roentgens) for each dosimeter irradiated. For conversion to dose or dose equivalent, the value of the exposure should be multiplied by the factors given in ANSI N13.11 or DOE/EH-0027. The reference(s) for the factor(s) used shall also be given.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART C.3 - NEUTRON IRRADIATION OF PERSONNEL DOSIMETERS

1. INTRODUCTION

The criteria contained in this part of the document apply to irradiation of dosimeters at radiation protection levels using neutron sources. These criteria are supplementary to the general criteria contained in part A and shall be followed if this specific irradiation service is offered and its inclusion in the Scope of Accreditation is desired. In that case, both the general criteria and these specific criteria shall be followed.

2. SCOPE

These criteria apply to irradiation of dosimeters used for personnel monitoring. They do not apply to dosimeters that use neutron activation foils to determine accident level doses.

3. SOURCE OF NEUTRON RADIATION

These criteria apply to neutrons from radionuclide sources, including sources in a moderator. They do not apply to accelerator produced neutrons or neutrons from reactors. Neutron sources specified by ANSI N13.11 or DOE/EH-0027 shall be available. Additional sources may be used if their spectral distributions, neutron emission rates, and dose equivalent conversion factors are well documented. The range of dose equivalents covered will be a function of the mission and requirements of the laboratory, but 150 mrem to 5 rem will suffice for most radiation protection purposes. All irradiations shall refer to free-field quantities and shall be performed with phantom backing.

4. CONTROL OF RADIATION FIELD

4.1 Shielding

The source storage container shall provide sufficient shielding such that leakage radiation does not interfere with other uses of the radiation room by raising the background level. Background radiation and leakage radiation from all sources in the radiation room shall not contribute more than 0.1% of the total dose equivalent to which dosimeters are irradiated.

4.2 Irradiation Control

A source transport system shall be provided to transport the source from the storage container to the irradiation position. Both the transit time from storage to irradiation position and the associated dose equivalent contribution to dosimeter irradiation shall be known.

It shall be possible to operate the source transport system with a timer. Any associated random timing uncertainties due to the transit time of the source shall be known. Any associated systematic timing uncertainties shall be measured and eliminated or compensated.

5. EQUIPMENT

In addition to one or more radiation sources and the associated source transport system, the laboratory shall have at least the following operable equipment available for calibration or irradiation use:

A phantom consisting of a slab of polymethylmethacrylate with a cross section of 40 cm × 40 cm and a thickness of 15 cm. The support system for the phantom shall be rigid and produce minimum scattered radiation at the dosimeter position(s). The system should provide for reproducible and accurate positioning of the phantom with respect to the radiation source.

6. CHARACTERIZATION OF THE RADIATION FIELD

6.1 Dose Equivalent Rates

The neutron radiation fields used for irradiation shall be characterized in terms of the free-field dose equivalent rate at the center of the front surface of the phantom. The neutron emission rate for each source shall be determined by the NIST. Procedures for determining the dose equivalent for dosimeters exposed to a ^{252}Cf source should follow Eisenhauer, Hunt, and Schwartz, "Calibration Techniques for Neutron Personnel Dosimetry," Radiat. Prot. Dosim. 10, 43 (1985). Procedures for other sources shall be documented. The contribution to the dose equivalent due to photon emission from the neutron source shall be measured and documented. There shall be verification of the expected dose-equivalent rate during irradiation.

6.2 Scatter

The contribution of air scattering, room return and source scattering shall be determined for all irradiation geometries and distances so that free-field dose equivalents can be determined. To minimize scatter, the irradiation room should be as large as is practically possible and irradiations should be conducted near the center of the room.

6.3 Accuracy

The dose equivalent rate specified by the laboratory as its reference value shall be within 5% of the actual value defined by comparison with the national standard. This level of agreement with the national standard shall be periodically verified through proficiency tests of the laboratory by NIST. A description of the proficiency test is given in Appendix A. The total uncertainty in the assigned neutron dose equivalent for irradiated dosimeters shall be less than or equal to 5%, excluding uncertainties in the dose equivalent conversion factors and the photon component of the neutron irradiations. To meet this criterion, it may be necessary to use position-specific correction factors when several dosimeters are irradiated simultaneously.

7. IRRADIATION CONDITIONS

7.1 Orientation

The dosimeters shall be attached to one of the two larger surfaces of the phantom, at least 10 centimeters from any edge of the surface, and that surface shall face the radiation source. That surface shall be perpendicular to a radial line from the source center to the phantom center. The position and orientation of the phantom shall be reproducible and verifiable.

7.2 Distance

The distance between the center of the radiation source and the center of the phantom surface to which the dosimeters are attached shall be at least 50 centimeters. The dose equivalent shall be calculated at the location of each dosimeter. It shall be reproducible and verifiable.

8. VERIFICATION OF DELIVERED DOSE EQUIVALENT

A method shall be used to verify the delivered dose equivalent independent of the timer and known dose equivalent rate. Possible verification methods include an off-axis detector or a passive detector exposed with each irradiation.

9. IRRADIATION REPORT

The laboratory shall report to the customer the free-field dose equivalent for each dosimeter irradiated. The ratio of the dose equivalent arising from photon emission by the radiation source to the neutron dose equivalent should be reported.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART C.4 - BETA-PARTICLE IRRADIATION OF PERSONNEL DOSIMETERS

1. INTRODUCTION

The criteria contained in this part of the document apply to irradiation of dosimeters at radiation protection levels using beta-particle sources. These criteria are supplementary to the general criteria contained in part A, and shall be followed if this specific irradiation service is offered and its inclusion in the Scope of Accreditation is desired. In that case, both the general criteria and these specific criteria shall be followed.

2. SCOPE

These criteria apply to irradiation of dosimeters used for personnel monitoring.

3. SOURCES OF BETA RADIATION

One or more sources of beta radiation shall be available for irradiation services. They may take the form of point sources or slab sources. The sources should meet the requirements of national or international standards (i.e., ANSI N13.11; DOE/EH-0027, ISO 6980). The dose range covered will be a function of the mission and requirements of the laboratory, but 150 mrad to 10 rad should be sufficient for most radiation protection purposes.

4. EQUIPMENT

In addition to one or more radiation sources and the associated beam control devices, the laboratory shall have the same minimum equipment as that required for gamma-ray calibration (see Part B.1, Section 4), with the exception of secondary standard ionization chambers. They shall be replaced by an extrapolation chamber or thin-window fixed volume ionization chamber that covers the energy and intensity ranges used for irradiation services. The laboratory shall also have a phantom consisting of a slab of polymethylmethacrylate with a minimum cross section of 30 cm by 30 cm and a minimum thickness of 5 cm. The support system for the phantom shall be rigid and produce minimum scattered radiation at the dosimeter position(s).

5. POINT SOURCES

5.1 Control of Radiation Beam

5.1.1 Shielding

The source storage containers shall provide sufficient shielding such that leakage radiation does not interfere with other uses of the radiation room by raising the background level. Background and leakage radiation from all sources of radiation within the room shall not contribute more than 0.1% of the total dose to which dosimeters are irradiated.

5.1.2 Beam Size and Uniformity

The beam size shall be sufficient to irradiate the entire phantom surface that is facing the source. If several dosimeters are irradiated simultaneously the beam shall be sufficiently uniform and characterized to satisfy the requirements of section 5.2.2. The use of an appropriate flattening filter may be required to achieve this.

5.1.3 Beam Emission Control

The irradiator shall have a built-in device to control emission of the beta radiation. It shall be possible to operate the emission control device with a timer. Any associated random timing uncertainties due to transit time of the device shall be known. Any associated systematic timing uncertainties shall be measured and eliminated or compensated.

5.2 Characterization of Radiation Field

5.2.1 Dose Rate

The beta radiation field used for irradiation shall be characterized in terms of dose rate at a depth of 7 mg/cm^2 in tissue.

5.2.2 Accuracy

The dose rate specified by the laboratory as its reference value shall be within 3% of the actual value defined by comparison with the national standard. This level of agreement with the national standard shall be periodically verified through proficiency tests of the laboratory by NIST. A description of the proficiency test is given in Appendix A. The total uncertainty of the dose delivered to an irradiated dosimeter shall be less than or equal to 5%. To meet this criterion, the use of a flattening filter and/or position-specific correction factors may be required when several dosimeters are irradiated simultaneously.

5.3 Source Containment

Source containment must be sufficiently sturdy to permit its safe and routine use. At the same time, it shall be sufficiently thin to ensure the beta particle energy spectrum of sources specified in ISO 6980.

5.4 Irradiation Conditions

5.4.1 Orientation

The dosimeters shall be attached to one of the two larger surfaces of the phantom, at least 5 centimeters from any edge of the surface, and that surface shall face the radiation source. The central axis of the collimated beam shall be perpendicular to that surface, and shall pass through its geometric center. The position and orientation of the phantom shall be reproducible and verifiable.

5.4.2 Distance

The distance between the radiation source and the phantom surface to which the dosimeters are attached shall comply with requirements in ANSI N13.11 or DOE/EH-0027. It shall be reproducible and verifiable.

6. SLAB SOURCES

Slab sources may be used when such irradiation geometry is more appropriate than a point source irradiation geometry.

6.1 Slab Size

The dimensions of the source shall exceed the dimensions of the irradiated dosimeter including all radiation sensitive elements.

6.2 Source Characteristics

6.2.1 The slab shall have a protective covering in the range of 3 mg/cm^2 to 7 mg/cm^2 inclusive. For uranium, the dose rate at 100 mg/cm^2 divided by the dose rate at 7 mg/cm^2 shall be 0.58 ± 0.04. The in-phantom dose rate at 1000 mg/cm^2 shall be less than three percent of the dose rate at 7 mg/cm^2. Appropriate dosimeters shall be used to confirm these relative dose rates.

6.3 Dose Rate

The beta radiation field on or near (< 1 cm) the surface of the source shall be characterized in terms of absorbed dose rate in tissue at a depth of 7 mg/cm^2. An extrapolation ionization chamber or a thin fixed volume ionization chamber shall be used to determine the dose rate.

6.4 Accuracy

The dose rate specified by the laboratory as its reference value shall be within 3% of the actual value defined by comparison with the national standard. This level of agreement with the national standard shall be periodically verified through proficiency tests of the laboratory by NIST. A description of the proficiency test is given in Appendix A. The total uncertainty of the dose delivered to an irradiated dosimeter shall be less than or equal to 5%.

6.5 Orientation

Dosimeters shall lie flat on the source surface or be suspended parallel to the surface with a maximum source-to-dosimeter distance of 0.5 cm.

7. VERIFICATION OF DELIVERED DOSE

For point sources, a method shall be used to verify the delivered dose independent of the timer and known dose rate. Possible verification methods include an off-axis detector, a small detector embedded in a corner of the phantom or a passive detector exposed with each irradiation.

8. IRRADIATION REPORT

The laboratory shall report to the customer the total dose (in rads or mrads) at 7 mg/cm^2 depth for each dosimeter irradiated.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART D.1 - GAMMA-RAY SOURCE CALIBRATION FOR EXPOSURE RATE

1. INTRODUCTION

The criteria contained in this part apply to the calibration of gamma-ray sources in terms of exposure rate in free air. These criteria are supplemental to the general criteria contained in Part A of this document, and are to be followed if this specific calibration service is offered and its inclusion in the Scope of Accreditation is desired. In that case, both the general and these specific criteria shall be met.

2. TYPES OF SOURCES CALIBRATED

These criteria are to allow sealed sources in transportable containers, which can be shipped easily, to be calibrated and shipped back to the user. The range of exposure rates shall be from 2 mR/h to 50 R/h measured at the 1 meter point in free air. The following sources shall be allowed for this type of calibration: ^{241}Am, ^{137}Cs, or ^{60}Co.

3. EQUIPMENT

The laboratory shall have at least the equipment specified in Part B.1, Section 4, as well as the following equipment dedicated to calibration use:

A source of gamma radiation greater than or equal to the activity of the radiation source to be calibrated. It shall have been calibrated in terms of exposure rate as a function of distance, and be subject to periodic quality assurance on at least an annual basis. Accreditation under Part B.1 precludes this requirement.

4. CONDITIONS OF CALIBRATION

4.1 Method

The calibration shall be performed by measurement of the source output using secondary standard ionization chambers or working standard ionization chambers that were calibrated against the secondary standards. The energy dependence of the standard chamber(s) shall be known over the range of photon energies to be measured.

4.2 Geometry

The source-detector geometry shall be carefully defined. Scattering (excluding that from the source and collimator) from the surroundings should be minimal and shall not exceed 10 percent of the exposure rate at any location where a detector is placed for source calibration. The approximate energy spectrum of scattered radiation should be known.

4.3 Attenuation

If an attenuator is used by the laboratory to deliberately reduce the exposure rate produced by the source, the effect of the attenuator on the energy spectrum of the gamma radiation should be known and the actual attenuation factor shall be determined by the laboratory. The effect of any electron fluence at the calibration position shall be considered.

5. SPECIFICATION OF SOURCE OUTPUT

5.1 Accuracy

The laboratory shall state the estimated uncertainty of the measured output of the source being calibrated, and this shall not exceed five percent total. This total uncertainty shall be calculated on the basis of a thorough analysis of possible errors. Accuracy shall be maintained through periodic intercomparison with a national standard.

5.2 Calibration Report

The calibration report shall include the following information for each source calibration:

(a) a complete description of the source-detector geometry used;

(b) the measured exposure rate at the distance(s) of calibration, with and without specified attenuators;

(c) a description of attenuator(s) used;

(d) the estimated uncertainty in the reported exposure rate.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART E.1 - X-RAY CALIBRATION OF INSTRUMENTS FOR DIAGNOSTIC LEVELS

1. INTRODUCTION

The criteria contained in this part of the document apply to calibration of instruments at diagnostic radiology levels using an x-ray source. These criteria are supplementary to the general criteria and shall be followed if this specific calibration service is offered and its inclusion in the laboratory's Scope of Accreditation is desired. Both the general criteria and these specific criteria shall be followed in that case.

2. SOURCE OF X-RAYS

The laboratory shall have a constant potential x-ray machine available for calibration of instruments. It should operate at potentials from 30 to 150 kV as a minimum range. The radiation field produced shall cover, as a minimum range, exposure rates from 20 R/h to 100 R/h, with a stability sufficient to calibrate instruments according to documented laboratory procedures. During calibration of an instrument, the exposure rate shall not vary by more than ± 1 percent.

3. CONTROL OF RADIATION BEAM

3.1 Beam Collimation

The x-ray beam emitted from the tube housing shall be collimated so that its size is limited to the minimum area consistent with calibration requirements.

3.2 Shutter

A shutter shall be used to control emission of the x-ray beam from the tube housing. If the beam is used for calibration of exposure-measuring instruments, the shutter transit time shall be known.

3.3 Exposure Control

If the x-ray beam is used for calibration of exposure-measuring instruments, the shutter shall be operated by a timer or a suitable charge integrating device. Any associated errors due to shutter transit times shall be known.

4. EQUIPMENT

In addition to one or more x-ray machines and associated control devices, the laboratory shall have the same minimum equipment as that required for gamma ray calibration (see Part B.1, Section 4) with the following exception - the secondary standard ionization chambers shall be appropriate to the energy and intensity of x rays for which calibration services are offered.

Additionally, the laboratory shall be equipped with filters to permit the production of a variety of x-ray beam qualities (see paragraph 5.4, below).

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Exposure Rate

The x-ray field used for calibration shall be characterized in terms of exposure rate at the location where the effective center of the instrument's detector is placed for calibrations.

5.2 Scatter

The contribution from scattered radiation shall not exceed 5 percent of the exposure rate at any location where a detector is placed for instrument calibration. The approximate energy spectrum of scattered radiation should be known.

5.3 Accuracy

The exposure rate specified by the laboratory as its reference value shall be within ± 5 percent of the actual value defined by comparison with the national standard. This level of agreement with the national standard shall be demonstrated through periodic proficiency tests of the laboratory by the National Institute of Standards and Technology (NIST). A description of the proficiency test is given in Appendix A.

5.4 Radiation Quality

The x-ray beam emitted from the tube housing shall be filtered before use for calibration purposes. The laboratory shall provide calibration services using at least five of the following radiation qualities:

Beam	First Half-Value Layer		Homogeneity Coefficient		Added Filter[1]	
Code	Al	Cu	Al	Cu	Al	Cu
	(mm)	(mm)			(mm)	(mm)
M30	0.36		64		0.50	
M50	1.02	0.032	66	62	1.021	
L80	1.83		58		1.284	
L100	2.8		59		1.978	
M100	5.0	0.20	72	55	5.0	
M150	10.2	0.67	87	62	5.0	0.25

[1] The added filter thicknesses relate specifically to the NIST beams, and are provided for guidance only.

For either aluminum or copper, the first half-value layer and homogeneity coefficients for a given x-ray beam shall be within five percent and seven percent, respectively, of the values shown in the above table. If necessary the indicated tube voltage or added filter, or both, may be adjusted to achieve those values. If a transmission chamber is used for routine beam monitoring, it shall be considered to be added filter material.

The intensity of the x-ray beam shall not vary more than five percent across the useful area of the beam.

The radiation quality shall be checked for stability at least annually. Whenever any part that could affect the beam quality is repaired or replaced the above requirements for radiation quality shall be met.

6. CALIBRATION REPORT

An instrument calibration report shall include, as a minimum, the x-ray beam used for calibration, the reference exposure rate or rates at which the instrument was calibrated, the exposure rate indicated by the instrument, and the correction factor at each calibration point. In the case of integrating instruments, in addition to the x-ray beam and exposure rate, the reference exposure, instrument reading, and correction factor shall be included. One calibration point and a linearity check should be included for each range of the instrument, where possible. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report. For instruments that use a vented ionization chamber, the reported values shall be referenced to a temperature of 22°C and a barometric pressure of 760 mm Hg, and the equation needed to convert to other temperatures and pressures shall be provided.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART F.1 - GAMMA-RAY CALIBRATION OF REFERENCE-CLASS INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of reference-class instruments at radiation protection levels using one or more gamma-ray sources. The reference-class instruments calibrated according to these criteria are intended for use by a customer and are not intended for use as working standards in the laboratory performing the calibration. These criteria are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if inclusion of this calibration service in the Scope of Accreditation is desired.

2. SOURCES OF GAMMA RADIATION

One or more of the following radiation sources shall be available for use in the calibration of reference-class instruments:

Radionuclide	Nominal Energy
^{137}Cs	660 keV
^{60}Co	1.25 MeV

The radiation fields produced by the sources should cover a range of exposure rates suitable for protection-level calibration.

3. RADIATION CONTROL

3.1 Shielding

Radiation barriers and/or storage containers for sources shall provide sufficient shielding so that background radiation in the calibration area is sufficiently low as to not interfere with ongoing calibration work.

3.2 Beam Collimation

The gamma radiation beam emitted from a source that has been exposed for calibration shall be collimated so that its size is limited to an area consistent with calibration requirements. An exception to this requirement is calibration facilities sufficiently large to provide a low scatter radiation environment for instrument calibration, e.g., an uncollimated source in a low scatter room.

3.3 Source Exposure

The source storage container shall have a mechanism to control exposure in the gamma beam. If the radiation source is used for calibration of exposure measuring (as contrasted with exposure-rate measuring) instruments, the shutter or source transit time and its effect on the total radiation exposure shall be known.

3.4 Exposure Control

If the radiation source is used for the calibration of exposure measuring instruments (see 3.3, above), the shutter or source transfer shall be initiated and terminated by a timer or the exposure shall be controlled by use of a transmission chamber. Any associated systematic timing uncertainties shall be documented and eliminated or compensated.

4. EQUIPMENT

In addition to one or more radiation sources and associated control devices, the laboratory shall have the same minimum equipment as that required for gamma-ray calibration (see Part B.1, Section 4).

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Exposure Rate

The gamma radiation field used for calibration shall be characterized in terms of exposure rate at a given position or distance from the source. The exposure rate shall be known at each distance used.

5.2 Scattered Radiation

The effect of scattered radiation (relative to a radiation field with minimal scatter) on the accuracy of calibration of each instrument type shall be known at each location where a detector is placed for instrument calibration. The approximate energy spectrum of the scattered radiation field should be known.

5.3 Attenuation

If an attenuator is used to reduce the exposure rate at any location in the radiation field, the effect of the altered radiation spectrum (relative to an unattenuated radiation spectrum) on the accuracy of calibration of each instrument type shall be known. The effect of any electron fluence at the calibration position shall be considered. The approximate energy spectrum of the attenuated radiation field should be known.

6. ACCURACY OF CALIBRATION

The chamber or instrument calibration factor specified by the laboratory for each source of radiation shall be within three percent of the true value as defined by comparison with a national standard. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

7. CALIBRATION REPORT

An ionization-chamber calibration report shall include, as a minimum, the radionuclide or photon energy used, the reference exposure rate or rates at which the chamber was calibrated, and the calibration factor of the chamber at each calibration point in terms of exposure per unit charge. Orientation of the chamber with respect to the radiation beam shall be described, the polarity and magnitude of the polarizing potential shall be stated, and the use of a build-up cap shall be noted.

An instrument calibration report shall include, as a minimum, the radionuclide or photon energy used, the reference exposure rate or rates at which the instrument was calibrated, the exposure rate indicated by the instrument, and the correction factor at each calibration point. In the case of integrating instruments, in addition to the radionuclide and exposure rate, the reference exposure, instrument reading, and correction factor shall be included. One calibration point and a linearity check should be included for each range of the instrument, where applicable. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report, and the use of a build-up cap shall be noted.

For a vented ionization chamber or an instrument that uses such a chamber, the reported values shall be referenced to a temperature of 22°C and a barometric pressure of 760 mm Hg, and the equation needed to convert to other temperatures and pressures shall be provided.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

PART F.2 — X-RAY CALIBRATION OF REFERENCE-CLASS INSTRUMENTS

1. INTRODUCTION

The criteria contained in this part apply to the calibration of reference-class instruments at radiation protection or diagnostic levels using an x-ray source. The reference-class instruments calibrated according to these criteria are intended for use by a customer and are not intended for use as working standards in the laboratory performing the calibration. These criteria are supplementary to the general criteria contained in Part A. Both the general criteria and these specific criteria shall be followed if inclusion of this calibration service in the Scope of Accreditation is desired.

2. SOURCE OF X RAYS

A constant potential x-ray generator shall be available for use in the calibration of reference-class instruments. Its maximum ripple shall not exceed two percent and it should be operable over a minimum range of 30 to 150 kV, 1 to 10 mA.

The radiation fields produced by the x-ray generator shall cover a range of exposures rates suitable for protection-level and diagnostic calibration. During calibration of an instrument, the exposure rate shall not vary by more than one percent from the nominal rate.

3. CONTROL OF THE RADIATION BEAM

3.1 Radiation Production

The production of a useful beam of radiation may be by means of the application of high voltage to the x-ray tube or the opening of a mechanical shutter (which normally acts as a shield to the x-ray beam).

3.2 Beam Collimation

The x-ray beam emitted from the tube housing shall be collimated so that its size is limited to an area consistent with calibration requirements. Provisions shall be made for identifying the central axis and boundaries of the useful area of the beam.

3.3 Exposure Control

If the radiation source is used for the calibration of exposure measuring instruments, the radiation beam shall be controlled by a timer or the exposure shall be controlled by use of a transmission chamber. The timing error due to the shutter transit times or high voltage ramping shall be known.

4. EQUIPMENT

In addition to one or more x-ray machines and associated control devices, the laboratory shall have the same minimum equipment as that required for gamma ray calibration (see Part B.1, Section 4) with the following exception - the secondary standard ionization chambers shall be appropriate to the energy and intensity of x rays for which calibration services are offered.

Additionally, the laboratory shall be equipped with filters to permit the production of a variety of x-ray beam qualities (see paragraph 5.3, below).

5. CHARACTERIZATION OF THE RADIATION FIELD

5.1 Exposure Rate

The x-ray radiation field used for calibration shall be characterized in terms of exposure rate at a given position or distance from the anode of the x-ray tube. The exposure rate shall be known at each distance used.

5.2 Scattered Radiation

The contribution to the exposure rate from scattered radiation shall not exceed five percent at any location where a detector is placed for instrument calibration.

5.3 Radiation Quality

The x-ray beam emitted from the tube housing shall be filtered before use to provide the appropriate radiation quality for calibration purposes. If a transmission chamber is used for routine beam monitoring, it shall be considered to be added filter material. Three or more of the beams shown in Table 1 (in Part B.2) shall be available.

The first half-value layer and homogeneity coefficients for a given x-ray beam shall be within five percent and seven percent, respectively, of the values shown in Table 1. If necessary the indicated tube voltage or added filter, or both, may be adjusted to achieve those values.

The intensity of the x-ray beam shall not vary more than five percent across the useful area of the beam.

The radiation quality shall be checked for stability at least annually. Whenever any part that could affect the beam quality is repaired or replaced the above requirements for radiation quality shall be met.

6. ACCURACY OF CALIBRATION

The chamber or instrument calibration factor specified by the laboratory for each x-ray beam shall be within three percent of the true value as defined by comparison with a national standard. This level of agreement with the standard shall be demonstrated through periodic proficiency testing by NIST. A description of the proficiency test is given in Appendix A.

7. CALIBRATION REPORT

An ionization-chamber calibration report shall include, as a minimum, a description of beam quality in terms of the codes in Table 1 or an equivalent method, the reference exposure rate or rates at which the chamber was calibrated, and the calibration factor of the chamber at each calibration point in terms of exposure per unit charge. Orientation of the chamber with respect to the radiation beam shall be described, and the polarity and magnitude of the polarizing potential shall be stated.

An instrument calibration report shall include, as a minimum, the x-ray beam used for calibration, the reference exposure rate or rates at which the instrument was calibrated, the exposure rate indicated by the instrument, and the correction factor at each calibration point. In the case of integrating instruments, in addition to the x-ray beam and exposure rate, the reference exposure, instrument reading, and correction factor shall be included. One calibration point and a linearity check should be included for each range of the instrument, where possible. The orientation of the instrument with respect to the radiation beam shall be described or illustrated in the calibration report.

For a vented ionization chamber or an instrument that uses such a chamber, the reported values shall be referenced to a temperature of 22°C and a barometric pressure of 760 mm Hg, and the equation needed to convert to other temperatures and pressures shall be provided.

CRITERIA FOR THE OPERATION
OF FEDERALLY-OWNED SECONDARY CALIBRATION LABORATORIES

APPENDIX A - NIST PROFICIENCY TESTS

Section 6.3 of the General Criteria (Part A) requires that a laboratory's proficiency be tested annually by the National Institute of Standards and Technology (NIST). Each proficiency test shall be representative of one or more types of calibration for which the laboratory is accredited. This appendix provides descriptive information about those required tests.

Table A1 identifies an appropriate proficiency test for each radiation quantity addressed in the various specific criteria contained in Parts B through F. If the quantity of interest, for example, is gamma exposure rate, the principal method for conducting the test is that NIST will calibrate an ionization chamber using an appropriate photon source, that same chamber will be sent to the participating laboratory for its calibration, and the calibration factor obtained by the latter will be compared with that obtained by NIST. If the difference between the two results is within the limit set forth in the specific criteria (usually in the "accuracy" section), performance of the laboratory is considered to be satisfactory.

For a laboratory that is accredited under the criteria of Part C.1 for irradiation of dosimeters, the proficiency test method may involve irradiation of test dosimeters by the participating laboratory, for subsequent readout by NIST to determine whether the delivered dose was within prescribed limits.

The proficiency test method for x-ray exposure rate is similar to that for gamma exposure rate. For beta dose rate, NIST will calibrate either an appropriate source or instrument, send it to the participating laboratory for its calibration, and compare calibration results. For neutron fluence rate or dose equivalent rate the principal method involves calibration of a remmeter, and alpha emission rate involves calibration of a suitable source.

One annual proficiency test may satisfy that requirement simultaneously for several specific criteria. If a laboratory is accredited, for example, to use a ^{137}Cs source for calibration of survey instruments (B.1), irradiation of personnel dosimeters (C.1), calibration of sources (D.1), and calibration of reference-class instruments (F.1), a single annual proficiency test could be sufficient for simultaneous satisfaction of the requirement for all four of those services. The most stringent performance level required in any one of these four specific criteria (three percent) would, of course, have to be satisfied by the single proficiency test.

It is not feasible that an annual proficiency test for a particular radiation quantity should attempt to cover the entire range of exposure rates, dose rates, fluence rates, or emission rates of interest. Instead, each annual test will involve only a representative part of the possible range, with the intent of covering the complete range over a period of years. Similarly, if a laboratory uses many of the x-ray beam codes, the annual proficiency test will not involve each code, but all codes will be covered in subsequent years.

There are a few cases where NIST does not have a radiation source similar to that used by a participating laboratory. In that case NIST will calibrate the proficiency test instrument with a surrogate source that has comparable characteristics. As an example, the ionization chamber used to test for gamma exposure rate will be calibrated by NIST with x rays instead of an ^{241}Am source if the participating laboratory wants to be accredited for using the latter. The energy spectrum of the x-ray beam used by NIST will approximate that from an ^{241}Am source.

TABLE A1. NIST Proficiency Tests for Various Radiation Quantities

Radiation Quantity (rate)	Source	Relevant Criteria	NIST Proficiency Test
gamma-ray exposure	^{241}Am	B.1	ion chamber calibrated with x-rays
		D.1	ion chamber calibrated with x-rays
	^{137}Cs	B.1	ion chamber calibrated with ^{137}Cs
		C.1	dosimeter or ion chamber calibrated with ^{137}Cs
		D.1	ion chamber calibrated with ^{137}Cs
		F.1	ion chamber calibrated with ^{137}Cs
	^{60}Co	B.1	ion chamber calibrated with ^{60}Co
		D.1	ion chamber calibrated with ^{60}Co
		F.1	ion chamber calibrated with ^{60}Co
x-ray exposure	NIST codes	B.2	ion chamber calibrated with appropriate beams
		C.2	dosimeter or ion chamber calibrated with appropriate beams
		E.1	ion chamber calibrated with appropriate beams
		F.2	ion chamber calibrated with appropriate beams
beta dose	^{147}Pm	B.3	calibrated ^{147}Pm source
	^{204}Tl	B.3	calibrated ^{204}Tl source
		C.4	calibrated ^{204}Tl source
	$^{90}Sr/^{90}Y$	B.3	calibrated $^{90}Sr/^{90}Y$ source
		C.4	dosimeter or calibrated $^{90}Sr/^{90}Y$ source
	^{99}Tc	B.3	calibrated ^{99}Tc source
	^{85}Kr	B.3	calibrated ^{85}Kr source
	U_{nat}	B.3	calibrated U_{nat} source
		C.4	calibrated U_{nat} source
	U_{dep}	B.3	calibrated U_{dep} source
		C.4	calibrated U_{dep} source
	$^{106}Ru/^{106}Rh$	B.3	calibrated $^{106}Ru/^{106}Rh$ source
neutron fluence or dose equivalent	$^{238}Pu(Be)$	B.4	remmeter calibrated with $^{241}Am(Be)$
	$^{239}Pu(Be)$	B.4	remmeter calibrated with $^{241}Am(Be)$
	$^{241}Am(Be)$	B.4	remmeter calibrated with $^{241}Am(Be)$
	^{252}Cf	B.4	remmeter calibrated with ^{252}Cf, bare
		C.3	dosimeter irradiated with ^{252}Cf, bare
	$^{252}Cfmod$	B.4	remmeter calibrated with ^{252}Cf, moderated
		C.3	dosimeter irradiated with ^{252}Cf, moderated
alpha emission	U_{nat}	B.5	calibrated U_{nat} source
	U_{dep}	B.5	calibrated U_{dep} source
	^{238}Pu	B.5	calibrated ^{238}Pu source
	^{239}Pu	B.5	calibrated ^{239}Pu source
	Th_{nat}	B.5	calibrated Th_{nat} source
	^{230}Th	B.5	calibrated ^{230}Th source

APPENDIX B - GLOSSARY OF TERMS

accuracy - the degree of agreement of an observed value (i.e., the value indicated by a measurement process) with the true value of the quantity being measured. When expressed in percent it is calculated as

$$\text{accuracy} = \frac{\text{observed value - true value}}{\text{true value}} \times 100 \quad .$$

accreditation - recognition of a laboratory's competence to perform calibrations in accordance with established criteria.

attenuator - absorbing material intentionally placed in the path of a radiation beam to reduce its intensity.

calibration (instrument) - comparison of the response of a given instrument with the response of a standard instrument when both are exposed to the same radiation source under the same conditions; or the determination of the response of the given instrument when exposed to a known radiation field under well-defined conditions.

calibration (source) - determination of the output of a radiation source by comparison with the output of a standard source, or by the response of a standard instrument to the output of the source.

collimator - a device used to limit the size, shape, and direction of a radiation beam.

constant potential - a unidirectional voltage of essentially constant magnitude.

correction factor - the ratio of the reference value of a radiation quantity to the value indicated by an instrument, i.e., $\frac{\text{reference value}}{\text{indicated value}}$. Multiplication of the indicated value by the correction factor yields the reference value.

criteria - documented minimum performance characteristics that must be satisfied by a laboratory in order to achieve accreditation.

critical equipment - any piece of equipment that has a unique calibration (correction) factor and is used by the laboratory to provide a calibration service. Examples are a radiation source, secondary standard, and an electrometer.

error - for a particular measurement result, the difference between the measured value χ and the true value τ (i.e., $\chi - \tau$).

extrapolation chamber - an ionization chamber in which the separation of electrodes is variable, thereby enabling a series of measurements with decreasing separation so that the measured ion current per unit volume can be extrapolated to the case of infinitesimal volume.

free-air facility - a calibration facility in which the radiation emitted by the source reaches the instrument under calibration with minimal scatter from nearby structures.

free-field quantity - a radiation quantity, such as neutron dose equivalent, that has been corrected to remove contributions from scattered radiation (e.g., air scattering and room return).

half-value layer (HVL) - the thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the value of a specified radiation quantity upon transmission through the substance by one-half.

homogeneity coefficient - the ratio of the first half-value layer to the second half-value layer, multiplied by 100.

instrumentation - a generic term that includes radiation sources and instruments or devices used to measure radiation levels.

ionization chamber - a gas-filled enclosure in which ion pairs created by incident radiation are collected on electrodes.

leakage radiation - radiation other than the useful beam emitted from an x-ray tube housing or a source container.

point source - a radiation source whose maximum dimension is small compared with the source-to-detector distance used for irradiation of a dosimeter or instrument.

proficiency test - a test of the performance of a laboratory by intercomparison of the results obtained from calibration of a common instrument or radiation source by both the laboratory under test and the laboratory conducting the test.

protocol - the documented policies and procedures used by a laboratory in conduct of calibration.

quality assurance - the general program of actions taken to ensure a satisfactory level of quality in the services provided by a laboratory.

quality control - the specific, technical procedures followed routinely to detect and correct any problems that would cause a laboratory to provide services at an unacceptable level of quality.

reference-class instrument - an instrument or ionization chamber that is sufficiently precise and accurate to serve as a tertiary standard.

reference value - the value of a particular quantity (e.g., exposure rate) that characterizes a laboratory's radiation field. It is the value to which the indicated value of an instrument under calibration is compared.

residual maximum beta energy, E_{res} - the maximum energy of the beta spectrum from all beta decay branches of a radionuclide at the calibration distance.

residual maximum beta range, R_{res} - the range in an absorbing material of a beta spectrum of residual maximum energy, E_{res}.

ripple - the periodic variation in the potential difference between the cathode and anode of an x-ray tube, resulting from rectification of an alternating current. As the ripple is decreased by the use of filtering circuits, a constant potential is more nearly approached.

scattered radiation - radiation that, as the result of interaction with matter, has had its direction changed and, for some interactions, its energy decreased.

scope of accreditation - a document issued by an accrediting organization that specifies the radiation types, energies, and intensities for which a laboratory is accredited to calibrate a particular type of instrumentation.

slab source - a radiation source whose maximum dimension is large compared with the source-to-detector distance used for irradiation of a dosimeter or instrument.

standard - a physical realization of the unit of a quantity, used as a reference for the calibration of an instrument or a lower-level standard.

national standard - a standard that serves as the primary reference for a specified quantity in a particular country.

secondary standard - a standard that was calibrated by direct comparison with a pertinent national standard.

tertiary standard - a standard that was calibrated by direct comparison with a pertinent secondary standard.

working standard - a standard that is calibrated periodically by direct comparison with an appropriate secondary standard, and is only used for routine calibrations of instruments.

support equipment - any piece of equipment, including critical equipment, used by the laboratory to provide a calibration service.

survey instrument - a hand-held instrument used to measure ionizing radiation for purposes of radiation protection. It does not include instruments designed as area, portal, or personnel monitors, as monitors of radioactive gases or airborne particulates, or as dose or beam calibrators for medical diagnostic or therapeutic applications.

thin source - a radiation source consisting of alpha-emitting radioactive material uniformly distributed in a thin layer over the surface of a flat metallic backing plate so as to cause minimal degradation of the alpha energy spectrum.

transmission chamber - a thin-walled ionization chamber designed to monitor a radiation beam that is transmitted through the chamber with minimal attenuation or scatter.

uncertainty - the estimated limits of the error in a measurement result.

random uncertainty - that uncertainty associated with error components that can be and are estimated by a statistical analysis of repeated measurements, and which indicate the degree of precision.

systematic uncertainty - that uncertainty associated with error components that are biased, and those which may be due to random causes but cannot be or are not assessed by statistical methods.

total uncertainty - an estimate of the likely limits of the error in a measurement result, obtained by combining all of the random and systematic uncertainty components.

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APPENDIX C

CALIBRATION - AN OVERVIEW

This chapter was originally published in Lalos, G., **Calibration Handbook: Ionizing Radiation Measuring Instruments**, Calibration Coordination Group DOD, Joint Technical Coordination Group for Metrology and Calibration (1983). As the title implies, it gives an overview for calibration procedures which are applicable for calibrating RADIAC equipment. In addition to the calibration procedures, there is a discussion of estimating uncertainties and how to propagate the individual components into a final value. The references include articles published in journals as well as textbooks and reports.

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CHAPTER 2

CALIBRATION - AN OVERVIEW

G. T. LALOS and H. T. HEATON II

2.1 INTRODUCTION

This chapter will be concerned primarily with calibrating instruments and will only cover those aspects of source calibration which impact on instrument calibration. The object of calibrating an instrument is to quantify its operating characteristics so that its use in a given measurement situation is made in as informed a manner as possible. Calibration of an instrument is accomplished by determining its actually measured responses or readings relative to a series of known radiation values over the range of the instrument. Source calibration may be accomplished by comparing the unknown source strength relative to that of a standard. Ionizing radiation measuring instruments are genarally calibrated in a known field or by a reference instrument technique. The accuracy of a measurement depends on the instrument's design, on the care taken in its calibration, and on good operating procedures such as frequent constancy tests during the time interval between calibrations, and on proper measurement techniques.

Proper instrument calibration requires that an assessment be made of its response not only to the type and energy of radiation for which the instrument was designed, but also to other radiations which may be present in practice and may contribute to the instrument reading. It also requires that mechanical and electrical integrity, and effects such as scale non-linearity, reproducibility, charge collection efficiency, pulse pile-up, charged particle equilibrium, and range-change errors be examined. Since manufacturers may not have cessary facilities for complete "type-testing" of instruments, it is desirable to check new instruments before use. A complete "type-test" will determine all the operating characteristics of the instrument with regard to radiation response, electrical characteristics and mechanical properties. A few examples of examinations which would be included in each of these three categories are for radiation: energy response, response to mixed types of radiation, location of effective center, ion current collection efficiency, and calibration or conversion factor; for electrical: reproducibility of meter movement, meter linearity, range-change characteristics, pulse pair resolution, and battery life; and for mechanical: geotropism, angular response of

instrument, and response to impact. More detailed information on "type-testing" of instruments can be found in IEC 395 (1972), IEC 463 (1974), IEC 325 (1970), and Bramson et al. (1976). A complete "type-test" need not be repeated for all instruments built to the same design. However, before any instrument is placed into operation, the calibration factor for specified radiation(s) should be determined, the scale linearity checked, the response on various measuring ranges (range-change error) determined, and the response to radiation overload measured. The initial calibration may involve either a wide or narrow energy spectrum. If a complete energy response curve is desired, a number of monoenergetic sources may be used. The choice depends on the purpose for which the instrument is to be used.

The characteristic of an instrument which is most likely to change over a period of time is the ratio of indicated value to "true" value, i.e., the reciprocal of the calibration factor. Some instruments provide an adjustment so that the reading can be brought back to the correct value when changes occur. In general, such adjustments should be made only at a calibration laboratory having the standards needed to re-check the instrument over its whole measurement range. The change in this ratio may not be linear over the entire range of the instrument. Some instruments are fitted with a switch position for testing the battery and there may be a zero adjustment. It should be realized that the battery test may not check all the batteries. If there is doubt, the batteries should be checked with an external battery tester (voltmeter and load for battery) before calibration. The use of constancy checks is clearly important. In general, the scope of periodic recalibrations should be the same as that of the initial calibration. However, the shape of the energy response curve is unlikely to change with time for most instruments. Thus, in actual calibration procedures, instruments are often checked on each range at only a few energies.

The purpose of a particular calibration procedure will determine the conditions under which it must be carried out. A distinction should be made between rigorously controlled tests in which the physical conditions are those appropriate for "type-testing" and other tests in which the response of an instrument is evaluated under conditions similar to those in which it is to be used. The conditions of calibration should always be stated clearly in reports. When instruments are purchased, the buyer should obtain information about the nature and accuracy of any calibration that the manufacturer may have made. Such information should be a part of the specifications furnished by the manufacturer or distributor.

2.2 ORGANIZATIONAL STRUCTURE

Meaningful instrument calibration requires standard reference instruments and/or sources, adequately equipped facilities, trained personnel, and explicit procedures for relating the response of the

calibrated instrument to a reference instrument or source. Ideally, all calibrated instruments should be capable of having their stated accuracy traceable to national standards kept at national standards laboratories. Because it is impractical for all users in a country to interact directly with that country's national standards laboratory, a multilevel system has evolved as shown in Figure 2.1 (Eisenhower, 1982).

In the United States, the national standards are maintained by the National Bureau of Standards (NBS). The NBS interacts directly with a number of highly competent Secondary Standards laboratories in the Private, Federal, and State Sectors (Figure 2.1). For ionizing radiation, examples of possible Secondary Standards laboratories in the Federal Sector include: National Laboratories (Los Alamos, Lawrence Livermore, etc.), Army, Navy, and Air Force Laboratories, National Center for Devices and Radiological Health, etc. In the State Sector, NBS is cooperating with several states to develop pilot Secondary Standards laboratories (Neuweg, 1980). Examples of possible Secondary Standards laboratories in the Private Sector include Battelle Pacific Northwest Laboratories which has calibration facilities comparable to National Laboratories, and the set of the American Association of Physicists in Medicine's Accredited Dosimetry Calibration Laboratories for calibrating field instruments used in radiation therapy (Shalek et al., 1980). Laboratories in the "Secondary Level" calibrate instruments which may be used directly for field measurements, or for reference standards at calibration laboratories in the "Field Use Level." A directory of commercial calibration laboratories has recently been issued (NBS GCR 80-296, 1981).

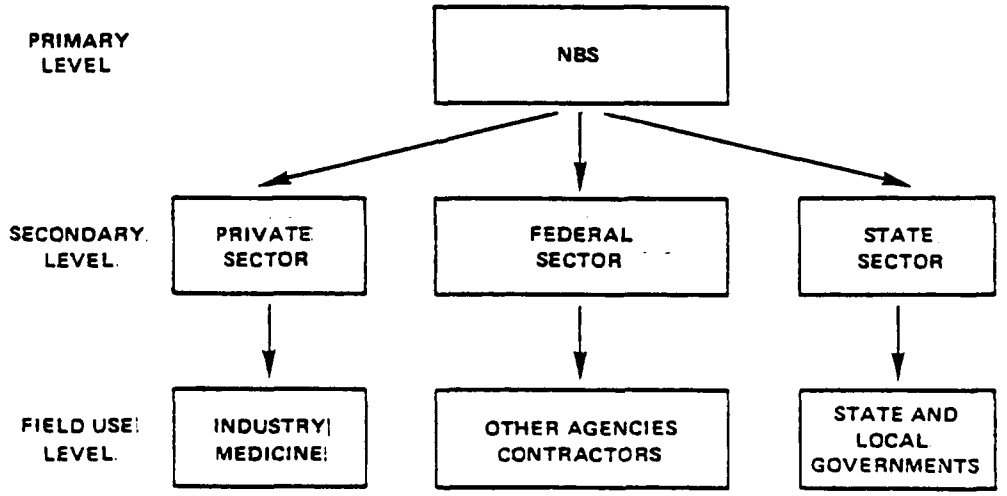

FIGURE 2.1 MULTI-LEVEL NATIONAL MEASUREMENT SUPPORT SYSTEM (EISENHOWER,1982).

2.3 RADIATION STANDARDS

2.3.1 Standards Hierarchy

It is possible to construct a standards hierarchy (applicable to both instrument and source calibrations) that corresponds to the organizational hierarchy shown in Figure 2.1. One of the problems with the conventional practice of calling standards "primary," "secondary," etc., it that the "primary" standard of the lower level in the hierarchy is often the "secondary" standard of the level above it in the hierarchy. The standards hierarchy given in Table 2.1 partially avoids this problem by simply labeling the standards used by organizations in the various levels as Level 1, 2, 3 or 4 standards. The table also lists uses of these standards and their associated uncertainty ranges in that level.

The uncertainty ranges given in the table include the uncertainties of all the levels higher in the chain. Thus, no standard maintained by a laboratory lower in the chain can have a total uncertainty smaller than the uncertainty assigned to the national standard for that quantity. Note, however, that with careful procedures it may be possible for a laboratory to make measurements relative to its standard with a statistical precision smaller than the overall uncertainty assigned to the standard. The overall uncertainty (systematic plus statistical) of measurements made by the calibration laboratory must be composed of a suitable combination of the uncertainty on its standard, the statistical precision of the measurement, and any biases in the measurement.

The actual values listed on the table of the uncertainties for standards for the various levels are to be taken as a guide and not as unchangeable values. In fact, there may be cases where greater accuracy is necessary for a given application than is shown in Table 2.1.

At present there is no unique set of criteria which can be applied to determine at what level in Figure 2.1 a particular calibration or measurement laboratory belongs. Criteria at the Secondary Level should at least include: an adequate quality control program to monitor internal performance, adequate documentation of procedures, participation with satisfactory results in a measurement quality assurance service provided by the National Bureau of Standards, and an overall estimate of uncertainties in the range shown in Table 2.1. Lacking these criteria, instrument and source manufacturers and commercial calibrators could fall into either Secondary or Field Level, depending on their calibration laboratory equipment and procedures. Table 2.1 reflects that at present NBS interacts directly with some users which might ultimately be in the Field Level when sufficient laboratories have been established in the Secondary Level for all the sectors.

TABLE 2.1 STANDARDS HIERARCHY

LEVEL	USE OF STANDARD	TYPICAL UNCERTAINTY (%)	COMMENTS
1	National Standard	x 1–2 γ 1–2 β 1–2(1) 5–10(2) α 1–2(1) n 1–5	Includes uncertainty on physical constants necessary to determine the quantity; represents latest state-of-the-art measurements.
2	1) Primary standard of Secondary Standards labs 2) Primary standard of organizations needing the highest level in-house standard	x 2–5 γ 2–5 β 5–15 α 2–10 n 5–15	Instrument and source manufacturers desiring calibration laboratories comparable to the Secondary Level labs in the Federal and state sectors will need the highest level standards available to them.
3	1) Primary standard for Field Level labs 2) Working standard for Secondary Standards labs	x 3–15 γ 3–15 β 10–20 α 3–20 n 7–20	These standards measured by Secondary Standards labs could serve as their working standards if they did not wish to use their primary standards for routine calibration.
4	Constancy standard	x 10–50 γ 10–50 β 15–50 α 15–50 n 20–50	The absolute value of these standards is not as important as being able to use them in a stable manner, i.e., instrument position, scattering, etc., remaining the same. It may be necessary to make corrections for source decay. These sources may be used by personnel at any level to monitor equipment performance.

(1) For radioactive sources calibrated in terms of activity or emission rate.

(2) For sources calibrated in terms of absorbed dose measured with an extrapolation chamber.

2.3.2 National Standards

In the United States the National Bureau of Standards (NBS) has the responsibility to establish, verify, maintain, and provide suitable measurement standards, and to perform calibrations and measurement quality assurance services to assure that ionizing radiation measurements made in the United States are in adequate agreement with national standards. Establishment of standards refers to the design, construction, and verification of measurement standards of a quality adequate to serve as primary national standards. Verification of these standards involves appropriate theoretical and experimental tests, and often intercomparison with comparable standards of other national and international

laboratories. Maintenance of standards refers to perodic tests of their constancy and reliability, both by means of internal tests and by occasional intercomparison with other countries. Standards are made available by calibration and transfer of suitable instruments and sources, as needed to meet the needs of the U.S., by providing "Standard Reference Materials" (SMRs) and by offering measurement quality assurance services to test the performance of users in obtaining measurement results that are consistent with the national standards to the accuracy needed.

The remainder of this section will deal with the physical quantities of greatest interest for ionizing radiation measurements and the corresponding national standards. The physical quantities are exposure, absorbed dose, activity and fluence. The standards are free-air chambers, graphite cavity chambers, calorimeters, extrapolation chambers, radium standards and a RaBe photoneutron source.

Emphasis is placed on the special nature of national standards, i.e., on the fact that these are standards that realize the unit of a quantity from its definition. This is in contrast to all other standards lower in the hierarchy which are calibrated by comparison with the national standards either directly or through the hierarchy chain.

The Free-Air Chamber (Exposure)

Exposure is the quotient of the total charge of electrons (or positive ions) produced when all the electrons liberated by photons interacting with a small volume of air are completely stopped, and the mass of that small volume of air. The free-air chamber measures the charge liberated when photons interact in air along the beam line. A uniform electric field perpendicular to the photon beam collects the ion pairs produced. Since the photons can interact any place along the beam line, proper operation of the free-air chamber depends on charged particle equilibrium (e.g., the amount of charge entering, produced, and leaving adjacent volume elements being equal) to achieve the appropriate charge measurement. The magnitude of the unit of exposure is established by measurement of the quantities Q (total charge collected), A (cross-sectional area of the photon beam), L (length of the collecting electrode), and ρ (density of air at the time of measurement), and the determination of a number of near-unity dimensionless correction factors. Thus, the free-air chamber is not calibrated, but rather its response is established from the above quantities and from the values of certain physical constants (Loevinger, 1976). The design and construction of free-air chambers is described in detail in a NBS handbook (Wyckoff, 1957).

A set of three free-air chambers is the national measurement standard of exposure for x-rays. They cover x-ray generating potentials 10 to 60 kV, 20 to 100 kV, and 60 to 250 kV. The three NBS free-air chambers have been intercompared among themselves a number

of times with agreement of 0.35% or better. Direct comparison with the primary standard chambers of several other national laboratories has shown agreement to better than 0.5%. Indirect comparisons of the NBS free-air chambers with other national standards have been made on several occasions at the Bureau International des Poids et Mesures (BIPM) by means of transfer standards. Again the NBS standards agreed within 0.5% with the BIPM standards and with the mean of the other national standards.

The Graphite Cavity Chamber (Exposure)

Practically, the use of the free-air chamber at atmospheric pressure is limited to photon energies less than about 300 keV. This limitation arises mainly from the fact that with increasing photon energy, the range of secondary electrons produced by the photon interactions increases, reaching a value of nearly 5 meters for the photons of Co-60. Since an atmospheric pressure free-air chamber for such photons would be far too large, high pressure free-air chambers were used at several national laboratories, and were studied at NBS (Wyckoff, 1960). An alternative approach is the use of graphite cavity ionization chambers as standards of exposure for the gamma rays of Cs-137 (0.66 MeV) and Co-60 (average: 1.25 MeV). The exposure measured from graphite cavity chambers depends on the measured volume of the cavity, the amount of charge collected, the density of air, some physical properties of the graphite and air (relative mass-energy absorption coefficients and relative mass stopping powers) and some other near unity correction factors.

The national standard for exposure for photons from Cs-137 and Co-60 is based on the averaged response of a set of six spherical chambers with active volumes from 1 cm^3 to 50 cm^3 (Loftus, 1969, 1974). All the chambers are made of high-purity graphite, including the central electrode.

Intercomparison of the chambers in a Co-60 beam typically shows agreement within 0.1% except for the 1-cm chamber whose response is 0.3% different from the mean response. In general, the agreement of the NBS standard graphite cavity chambers with the mean response of standard cavity chambers of other countries is the same as for free-air chambers, i.e., agreement is within about 0.5%. An uncertainty of 0.7% is assigned to the exposure graphite cavity ionization chambers (Loftus, 1974).

Graphite Calorimeters (Absorbed Dose)

Absorbed dose applies to both photon beams (x, and gamma radiation) and particle beams (beta rays, neutrons, etc.). It is defined in terms of the mean energy imparted per unit mass at the point of interest in some stated material (ICRU 33, 1980). Energy imparted to matter results in a rise in temperature, and the national standard for realization of the unit of absorbed dose in terms of its definition is a calorimeter. The special name for the unit of

absorbed dose is gray (Gy), where 1 Gy = 1 J/kg. The special unit of absorbed dose, 1 rad = 10^{-2} Gy, is presently allowed, but the ICRU recommends (ICRU 33, 1980) that the SI unit be used after 1985.

NBS has two high purity graphite calorimeters for determining absorbed-dose. The first is of graphite with dimensions of 40x40x30-cm and is permanently located in one of the experimental areas of the NBS 100-MeV linear accelerator. The "portable" calorimeter is in a 15-cm diameter by 10-cm deep graphite cylinder. These two calorimeters use a "heat-loss-compensation" principle, which provides a method of measuring nearly all the heat lost from the central core to its surrounding jacket at the time of calibration (Domen, 1974).

Interpretation of the response of a calorimeter is in principle simpler than interpretation of the response of a cavity ionization chamber. On the other hand, the calorimeter is considerably more delicate and complex to build than is a cavity chamber. A comparison of their sensitivities is instructive: an absorbed dose of 3 Gy (300 rad) produces a temperature rise of about 4 mK per gram (4×10^{-3} °C) in graphite; an exposure of about the same magnitude, 75 mJ/kg (300 R) liberates in air about 100 nC of charge in an ionization chamber with a volume of 1 cm^3. Thus, if we desire to measure this magnitude of radiation with a precision of 0.1%, we must in effect be able to detect differences of 4μK (4×10^{-6} °C) per gram for the calorimeter, and about 100 pC of charge for the ionization chamber. This charge measurement is not too difficult, but such a temperature measurement requires skill, as well as complex, sensitive, and expensive equipment. Clearly, a calorimeter is simpler in principle, but considerably more complicated in practice than an ionization chamber. This, of course, is why the ionization chamber is used for routine dosimetry, and why the calorimeter is not.

The two NBS calorimeters were intercompared in 20 MeV and 50 MeV electron beams of the NBS linear accelerator, and were found to agree to within 0.1-0.2% (Domen, 1976). The NBS portable calorimeter has been compared with ionometric standards of absorbed dose in graphite phantoms, both at NBS and at BIPM, and the two methods agree to about 0.3%, which is well within the uncertainties associated with the physical constants necessary for the comparison, namely the stopping-power ratio and the mean energy expended in air per unit charge.

Extrapolation Chamber (Absorbed Dose)

Calibration of the electron beams in the 30-100 MeV energy range can be performed calorimetrically, i.e., with graphite calorimeters as discussed above. For beta sources, which result in much smaller absorbed doses than the electron beams, there is insufficient temperature change to permit use of existing calorimeters. For these sources, the national standard is an extrapolation ionization chamber.

The most versatile ionization chamber for this purpose is a

plane-parallel plate ionization chamber in which the air gap between the collecting electrode and the polarizing electrode can be varied and the results extrapolated to zero volume. The chamber now in use at NBS is a modification made by J.S. Pruitt to an instrument described some years ago (Loevinger, 1966). The air gap in this chamber can be varied from about 0.05 mm to 20 mm. The collecting electrode can readily be changed, and a number of such electrodes are on hand. These are made of various low-atomic number materials, with collecting areas that vary from about 1 mm to 30 mm in diameter. Calibrations performed with the extrapolation chamber are reported in terms of absorbed dose by interpreting the ionization current in terms of the Bragg-Gray equation, using conventional values for the mean energy expended per unit charge, and for the stopping-power ratios.

Radium Standards

NBS has two primary radium standards. They were prepared by Prof. O. Hönigschmid in 1934, in the form of a weighed amount of a radium salt sealed in glass. They were compared with other primary Hönigschmid standards in Paris and Vienna in 1936. A number of platinum-iridium sealed radium sources were calibrated against the NBS Hönigschmid standards to serve as working standards since radium sealed in glass is not a very practical source for routine work. Intercomparison in 1955-57 between the United States, British, Canadian, and German primary standards showed these to be within about 0.2% agreement (Loftus, 1957).

Standard Photoneutron Source

The national standard photoneutron source, NBS-I, is the primary artifact standard for all fast-neutron source strength determinations and related measurements of neutron fluence rates. NBS-I is a radium-beryllium (gamma,n) source containing one gram of radium. The radium, enclosed in a cylindrical platinum-iridium can 8.4 mm dia. by 8.6 mm high with 0.2 mm wall thickness, is at the center of a 40 mm dia. sphere of beryllium (Curtiss, 1949). The beryllium sphere is enclosed in a thin aluminum jacket. The emission rate has been determined, using a heavy water solution of manganous sulphate (Noyce, 1963), to be 1.257×10^6 neutrons per second with an accuracy of approximately 1.0% (1 σ). Its decay rate is 0.04% per year. Intercomparison with similar neutron sources results in agreement of approximately 0.6% (1 σ). A second source, called NBS-II, has been used for intercomparisons, and is identical to NBS-I except that the radium is enclosed in a 1.0 mm thick monel capsule.

2.3.3 Transfer Standards

All standards that are below the national standards (Level 1) in the standards hierarchy (Table 2.1), are referred to as transfer standards since they transfer the standards from the higher level in the hierarchy to lower levels in the hierarchy. Note that only Level 2 standards are calibrated by direct comparison with the national standards.

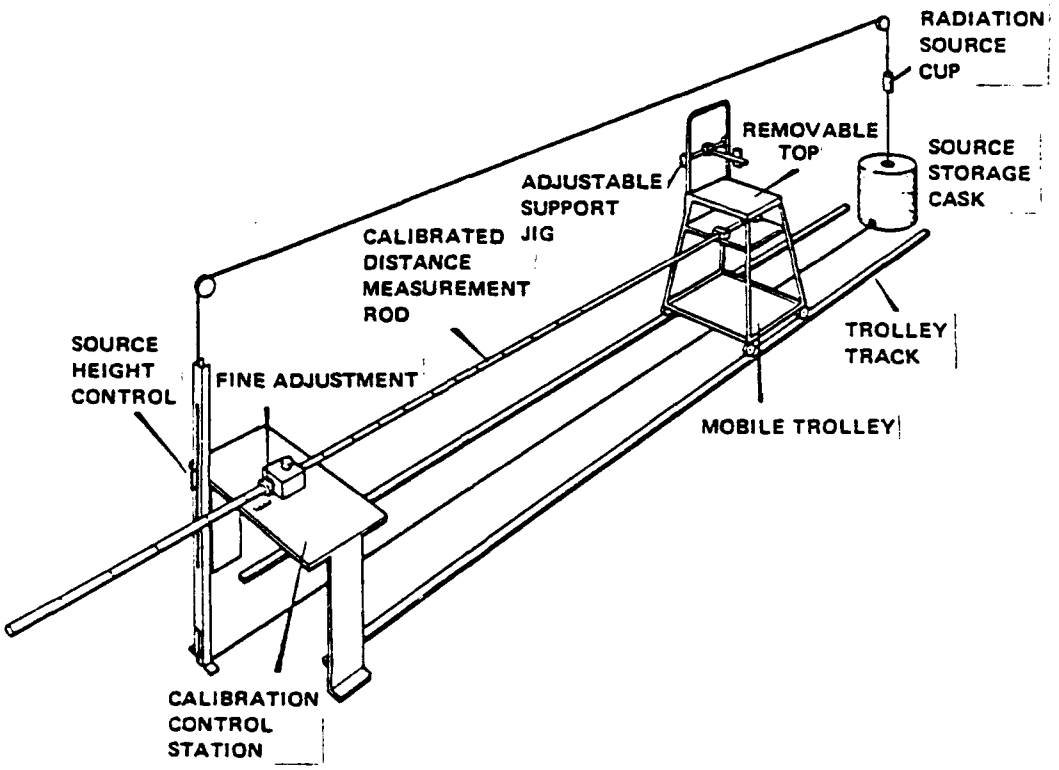

FIGURE 2.2 TYPICAL STAND AND EQUIPMENT FOR GAMMA CALIBRATION (BRAMSON, 1976).

2.4 INSTRUMENT CALIBRATION

2.4.1 Basic Calibration Techniques

There are two commonly used techniques for calibrating ionizing radiation measuring instruments. In the first technique the "unknown" instrument's response is determined in a known radiation field. In the second technique, the "unknown" instruments response is compared against that of a calibrated reference instrument. The latter technique can be subdivided into two parts:

1) substitution method in which the reference instrument and the unknown instrument are sequentially placed in the radiation field (this requires the field remaining constant); and 2) simultaneous method in which both the reference and unknown instrument are placed in the radiation field at the same time (this results in possible instrument cross-scattering problems). A typical calibration stand for routine gamma calibration, suitable for either technique is shown in Figure 2.2.

Known Field Technique

In this technique the radiation field is characterized from knowledge of certain parameters of the source or characterized by a known output rate determined at a specified distance. In either case, if the standard source approximates a point source, and if scattering and air attenuation are negligible, the inverse-square law can be used to calculate field strength as a function of distance from the source. Radioactive sources used for instrument calibration are generally calibrated for exposure rate at a given distance, for activity, or for emission rate (source strength). It is necessary to make an explicit correction for source decay. Machines used as known sources must have radiation monitors calibrated with a reference instrument for various machine operating conditions. Once the monitor has been calibrated, the field at the calibration point is then known in terms of the monitor response.

Reference Instrument Technique

The reference instrument technique employs either the substitution method or the simultaneous method. In calibrating instruments using the substitution method a reference instrument is placed in the radiation field and its response noted. This instrument should have been calibrated at the same energy as the radiation field in use. The instrument being calibrated is then substituted for the reference instrument (effective centers at same position) and the calibration made by comparing the two readings. In the simultaneous method the "unknown" instrument and the reference instrument are placed in the radiation field of the calibration source at the same time and the response of the two instruments noted. The two instruments should be separated sufficiently to minimize instrument cross scattering, but not so much as to result in one or both of the instruments being outside the region of uniform field strength. The reference instrument technique should always be used when the field strength of the calibration source is not accurately known.

Calibration Wells

In many practical situations, it is necessary to calibrate a large number of the same model of survey instrument. In this case one

is interested in using a method in which the instruments can be quickly calibrated. One such method is to use a calibration well. The correct use of a calibration well depends on a slight modification of the reference instrument technique.

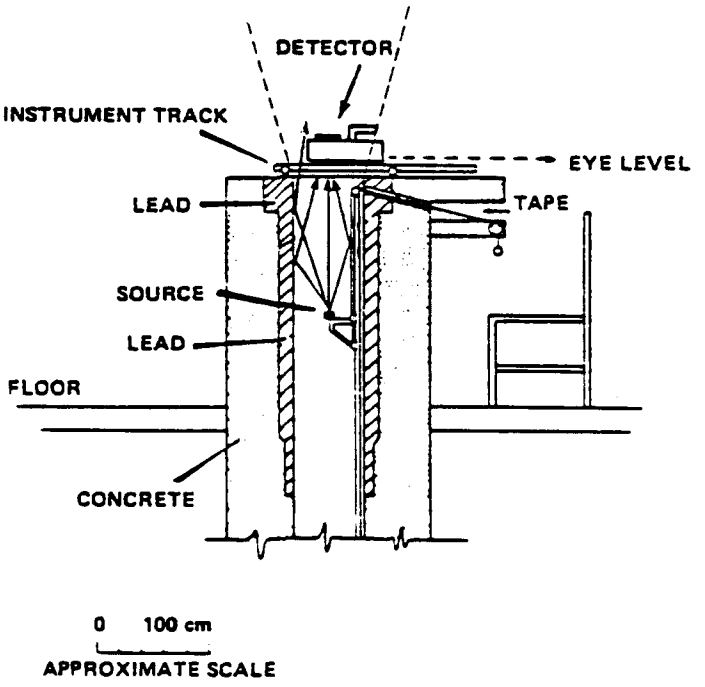

FIGURE 2.3 TUBE-TYPE CALIBRATION WELL.

To understand the reasons why the reference instrument technique must be modified, the general features of calibration wells will be reviewed. Calibration wells are usually in one of two geometries. Figure 2.3 shows a "tube" type calibration well. The intensity is varied by adjusting the height of the source in the tube. Note that radiation is scattered in the well and a portion of it can be incident on the detector. The "box" type calibration well is shown in Figure 2.4. In this case the intensity is varied by placing attenuators of various thickness in the beam line. The survey instrument is placed in a small volume so again there is scattered radiation incident on the survey instrument.

It is this scattered radiation which necessitates a modification of the reference instrument technique. This scattered radiation will have a different energy spectrum than the primary radiation. If the reference instrument has an energy dependence, the scattered radiation will result in an error in the determination of field strength. To minimize the effects due to the scattered radiation one would like to have a "reference" instrument identical to the instrument to be calibrated. In this case, the scattering of radiation both inside the instrument and in the well would be

identical and the energy response of both the reference instrument and the survey instrument would be the same. This can be accomplished by selecting one of the survey instruments and designating it as a "reference" or pseudo-reference instrument. This "reference" instrument is then calibrated in scatter-free conditions (by either using the normal reference instrument technique or using a known field technique). The "reference" instrument is then placed in the well and its response noted. All other instruments of the same type are then placed in the well and each response compared against that of the "reference" instrument.

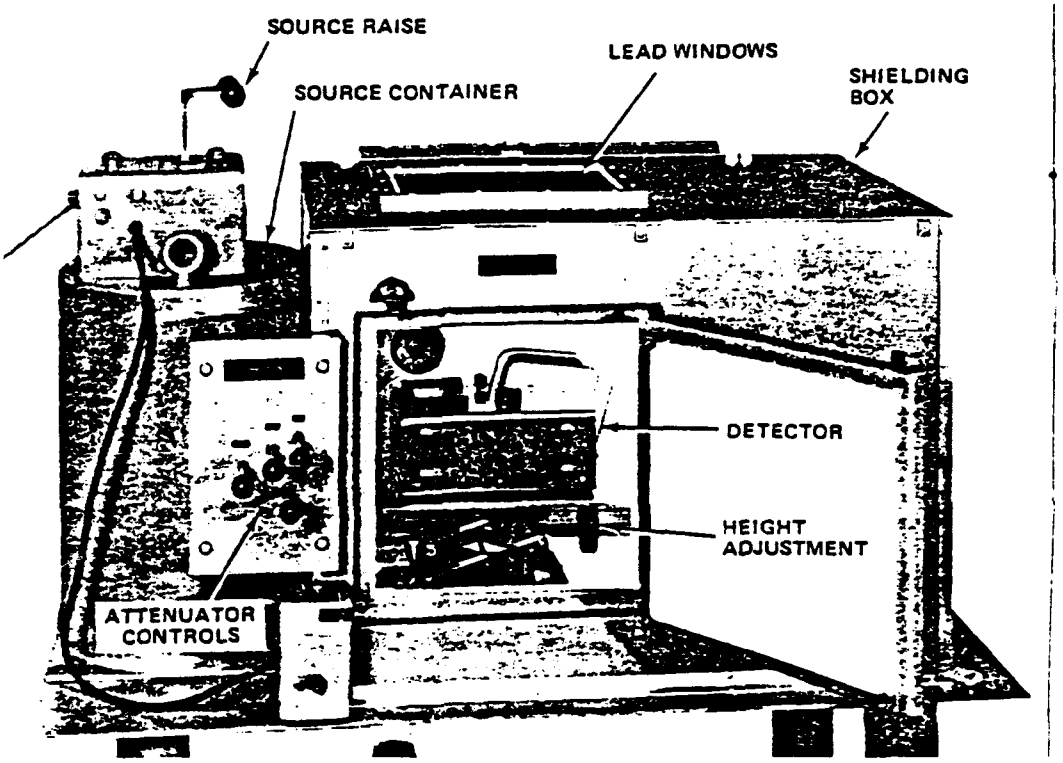

FIGURE 2.4 BOX-TYPE CALIBRATION WELL.

Two points are essential for this method to work. First, the calibration for the "reference" instrument is the scatter-free calibration. The calibration well merely provides a convenient source of radiation. Second, the reference instrument should be essentially identical to the survey instrument being calibrated.

2.4.2 Calibration Adjustments and Corrections

The correction factor determined in the calibration process is transferred to the instrument by one of the following three procedures.

Equipment Adjustment In this procedure the test instrument

calibration controls are adjusted until the display reads correctly, i.e., reads the actual value of the radiation field (known-field technique), or gives the same reading as the reference instrument (reference instrument technique). A typical example would be the adjustment of a "Cutie Pie" ionization chamber instrument (Chapter 3) in a 100 mR/hr Cs-137 gamma radiation field to display this value.

Cross-Reference Table This procedure does not involve any instrument adjustments. The observed display readings are recorded as a function of known reference field strength (for both known field and reference instrument techniques) and this information is used to generate tables of corrected field strength (or correction factors) versus display reading. Typical examples would be pulse output from a GM counter in terms of roentgens, or channel number versus energy for gamma spectrometry.

Tolerance Certification This procedure is used mostly by calibration laboratories that handle large numbers of inexpensive but reuseable personnel dosimeters. Depending on the device and its intended use, a value of the desired accuracy is chosen. If the device registers a reading outside of the chosen tolerance level it is discarded. If it indicates a dose within the chosen tolerance level it is certified as being calibrated. For example, if during a test of 100 randomly chosen TLDs (Chapter 8) two or three are outside the tolerance level they are removed from use and discarded. Thus, calibration has been performed in that the remaining TLDs will read within a given percentage of actual dose.

2.4.3 Calibration Sources and Techniques

Before an instrument is calibrated, appropriate operational checks should be made. The type of radiation field that the instrument is to be used in will influence the initial tests that are made in the instrument and possibly the energy at which it is calibrated. A description of precalibration checks is given in Section 2.6.

X- and Gamma-Ray Calibration

The calibration of photon monitoring instruments over the energy range from a few keV to a few MeV is normally performed using x-ray generators and radionuclide sources. Different field strengths should be available to accomodate the different types and ranges of instruments undergoing calibration. Field strengths may cover the range from natural background levels up to a few thousand R/hr.

At energies below 300 keV instrument calibration is normally performed in terms of exposure using an x-ray generator with a collimated beam and an ionization chamber as the reference instrument. The ionization chamber in itself should be calibrated in the next higher level in the standards hierarchy. Calibrations using x-ray generators normally employ the substitution method in order to

minimize the necessity of corrections (scattering, etc.).

When instrument calibration is performed using an x-ray generator and the substitution method is emloyed one must be certain that there is no change in the x-ray beam exposure rate or spectral quality when the reference instrument is replaced by the instrument being calibrated. A monitor helps ensure that no changes have occurred (IAEA 133, 1971).

Many exposure measuring instruments have a response that is very energy-dependent, especially at photon energies below 100 keV. When studying the energy dependence of an instrument it is important that the x-ray spectrum used be as narrow as possible (Shambon, 1962). The spectrum of an x-ray beam can be substantially reduced in width and hardened (maximum intensity shifted to higher energy) by using appropriate absorbers made of high purity materials. For energy dependence measurements below 100 keV the K-fluorescence emission of different elements can be used as an almost monoenergetic source of radiation (Storm, 1965; Shambon, 1963). The improved energy definition obtained with K-fluorescence radiation over the use of heavily filtered x-ray beams is generally not necessary for radiation protection purposes. For given x-ray tube voltages, recommended filter material and radiator material can be found in ISO 4037, (1979). Alternatively, the same beam filters used in calibration at NBS (see appendix of NBS SP 250, 1982) could be adopted.

TABLE 2.2 PHOTON EMITTING RADIONUCLIDES SUITABLE FOR USE IN INSTRUMENT CALIBARATION

RADIONUCLIDE	EFFECTIVE ENERGY (keV)	HALF-LIFE	EXPOSURE RATE CONSTANT R/(hr·Ci) at 1m
^{125}I	35	60 Days	0.0044
^{241}Am	60	433 Years	0.0129
^{57}Co	122	270 Days	0.097
^{114m}In	192	50 Days	0.043
^{203}Hg	279	47 Days	0.12
^{51}Cr	320	28 Days	0.018
^{198}Au	412	2.7 Days	0.23
^{137}Cs	662	30.0 Years	0.323
^{226}Ra	830	1600 Years	0.825[1]
^{60}Co	1250	5.27 Years	1.30
^{24}Na	2061	15 Hours	1.84

[1] For radium in equilibrium with its daughter products filtered by 0.5mm of platinum.

REFERENCES: Nachtigal, 1969; Lederer, 1978; Nuclear Data, 1966-73; Kocner, 1981.

The effective energy of an x-ray beam can be determined from the half-value layer (HVL). This is accomplished by experimentally determining the absorber thickness (usually aluminum or copper) required to reduce the beam exposure rate by 50% under scatter-free conditions. The effective energy is the energy of a monoenergetic x ray which has the same half-value layer as the x-ray beam (ICRU, 1964; Trout, 1960).

From energies of 300 keV up to a few MeV, radionuclides are generally the best choice of radiation sources for calibration. Co-60, Cs-137 and Ra-226 are most common, but other radionuclides are available, including some providing photons in the range of energies produced by x-ray tubes. Radionuclides suitable for use in instrument calibration are shown in Table 2.2. Such sources often are calibrated (ICRU 12, 1968) in terms of exposure rate at some specified distance, and proper allowance must be made for subsequent decay. Alternatively, exposure rates due to a source can be calculated from its radioactive content using the exposure rate constant. This constant includes x rays from the source. Otherwise it is the same as the previously defined (Chapter 1) specific gamma ray constant (Nachtigall, 1969). When calculating the exposure rate at a fixed distance, it may be necessary to allow for attenuation of the radiation in the source and its encapsulation.

Ideally, a radionuclide source should emit photons of a single energy and have a long half-life. In practice, however, although emission at a single energy may be the best choice for determining response, a calibration source with similar emission characteristics as the source to be monitored would be preferable for overall instrument response. The instrument and sources should be positioned well above ground on stands which introduce very little additional scatter, i.e., the stands should be constructed from a minimal amount of low-atomic number materials (Al or plastic). See Figure 2.2 for a typical calibration stand and equipment for routine gamma calibration (IAEA 133, 1971).

The radiation exposure rate used to check scale linearity in the calibration may be varied by changing the current in the x-ray tube (provided that the tube potential is kept constant), by use of nuclide sources of different activities, or by changing the distance between source and instrument. The inverse square relation may be used in many cases, but the validity of such a procedure should be established since departures from this relationship will occur when source dimensions are comparable with the source-detector distance or where scattered radiation or air attenuation is great. The validity of the inverse square assumption may be varified by measurements made with a physically small detector, thereby reducing ambiguities about the reference point of measurement.

The sensitivity of a radiation detector may vary with the angle of incidence of the radiation. One can study this effect by calibrating the instrument at various angles to the incident radiation for different energies of the radiation. Similarly, a measuring instrument designed to be worn on the surface of the body

may differ in its response as the angle of incidence of the radiation changes.

Variations in ambient temperature and pressure will have an effect on an instrument's calibration for instruments vented to the atmosphere (e.g., air ionization chambers). In temperate climates, or under laboratory conditions, and near sea level such effects may be unimportant. If, however, the instrument is to be used at high altitudes or outdoors in very hot or cold climates, correction factors for these conditions should be made. High humidity may also have adverse effects on instrument performance, expecially on insulators, or other high impedance components. Instruments with a zero-set control often enable compensation for environmental effects on electronics. If the instrument is to be used in ambient conditions which differ greatly from normal, then environmental tests should be made to assess the likely errors so that correction factors may be applied to the readings if required.

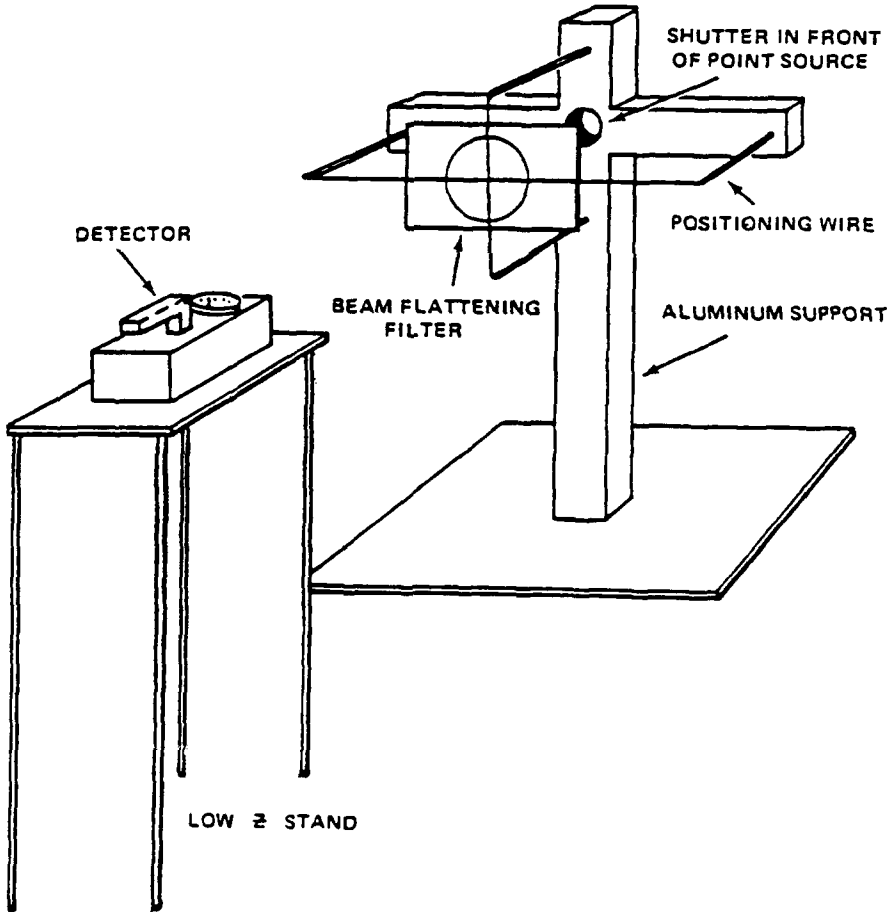

FIGURE 2.5 POINT SOURCE β RADIATION CALIBRATION FACILITY.

Beta-Ray Calibration

Calibrating instruments for beta radiation and the interpretation of readings made with such instruments are difficult. The beta particles for a given radionuclide have a spectrum of energies up to some maximum. Hence, they are usually characterized by both an average energy and a maximum energy. For materials other than gases, the range of the beta particles is usually less than a few cm. Calibration of an instrument can be determined with a source of beta radiation which has been calibrated with an extrapolation chamber (IAEA 133, 1971; Loevinger, 1966). Instruments responding to beta particles will also respond to x and gamma radiation and to secondary electrons generated by them in air or in the instrument.

TABLE 2.3 BETA RADIATION SOURCES FOR INSTRUMENT CALIBRATION (IN ORDER OF INCREASING E_{max})

RADIONUCLIDE[1]	E_{max} (MeV)	E_{avg} (MeV)	PERCENT	HALF-LIFE
^{3}H	0.0185	0.0057	100	12.35 Years
^{14}C	0.156	0.049	100	5.730 Years
^{35}S	0.167	0.049	100	88.0 Years
^{147}Pm	0.224	0.060	100	2.62 Years
^{45}Ca	0.257	0.077	100	164 Days
^{99}Tc	0.294	0.085	100	2.13×10^{5} Years
^{60}Co	0.3179	0.0959	99.9	5.271 Years
^{185}W	0.433	0.144	100	75 Days
^{85}Kr	0.674	0.246	99	10.7 Years
^{204}Tl	0.763	0.243	98	3.78 Years
^{111}Ag	1.03	0.351	93	3.78 Days
^{210}Bi	1.16	0.394	100	5.01 Days
^{32}P	1.71	0.695	100	14.3 Days
$^{90}Sr-^{90}Y$	2.27	0.566	99	28.5 Years
^{238}U	3.26	——	——	4.49×10^{9} Years
^{42}K	3.25	1.43	82	12.4 Hours

[1]Notes: Some sources accompanied by γ rays.
References: Lederer, 1978; Nuclear Data, 1966-73; Kocher, 1981.

To obtain uniform radiation fields, calibrations are commonly made with the detector window nearly in contact with a large area, flat, uniformly distributed source made of natural uranium, U-238 or Sr-90 (Cember, 1969; Gale and Peale, 1963) or at a given distance from a small source with suitable beam flatteners (Owens, 1972). Figure 2.5 shows a typical point source β radiation calibration facility. Table 2.3 includes a list of beta sources which are suitable for instrument calibration. Some of these sources also emit photons. The instrument response to these photons, together with any bremsstrahlung from surrounding materials, should be taken into consideration in the calibration. Instruments for measuring beta

particles are usually calibrated in terms of absorbed dose to air or to tissue. The energy dependence of instruments will be less if its walls and end window are constructed of air or tissue-like material.

Alpha-Ray Calibration

Alpha sources are used for the calibration of instruments used in the field for monitoring surface contamination. Alpha-ray sources are commonly prepared by electroplating a metallic alpha-ray emitter such as uranium or plutonium onto a disc or a suitable metal such as stainless steel. The emitter may also be thinly deposited on a low Z material so as to have minimal self absorption and backscatter. The prepared source is assayed, in terms of emission rate into a known solid angle by the use of a standard counter. This is frequently either a windowless proportional counter, a proportional counter, a proportional counter with an extremely thin window, or a solid state detector. The sample itself absorbs some portion of the alpha particle energy due to its finite thickness and, where there is an appreciable path length between source and detector, geometrical straggling is also a factor. These sources themselves are usually standardized with a precision of better than 2 % by comparison with a suitable reference source standard in a counting laboratory.

Table 2.4 lists energies, abundances, and half-lives of sources suitable for calibration of alpha-ray measuring instruments. Pu-239 and natural uranium are two of the most commonly used radionuclides for calibration purposes. They are usually used as a thin metallic foil (natural uranium) or by electroplating a metallic alpha solution onto stainless steel, platinum, or other suitable metal. These preparation methods provide a uniform distribution of alpha emitter and minimize loss of activity. Evaporation of solutions is unsatisfactory for producing standard sources, for the activity tends to come away from the backing and uniform distribution of activity is virtually impossible to achieve. Because of the short range of alpha particles, standard alpha sources usually are uncovered and must be handled carefully, both from a health standpoint and to avoid loss of activity.

Inasmuch as several of the sources listed in Table 2.4 also emit photons or betas along with the alphas, instrument response to all emitted radiations must be considered when selecting a source. Ideally, the calibration source should be the same nuclide as the one the instrument is intended to measure, but this may be impractical if the instrument will be used for many (and not necessarily known) nuclides or for general alpha contamination surveys.

If only a single nuclide were to be selected as a standard source for alpha contamination survey meters, Pu-239 probably would be the choice, although safeguarding precautions (i.e., need to inventory) may be necessary. The energy of alphas emitted by this nuclide, approximately 5.1 MeV, is roughly in the middle of the range of energies of most common alpha emitters (4.1 - 6.1 MeV) and in

TABLE 2.4 ALPHA RADIATION SOURCES FOR INSTRUMENT CALIBRATION
(IN ORDER OF INCREASING ENERGY)

RADIONUCLIDE	ALPHA ENERGY (MeV)	PERCENT	HALF-LIFE
^{148}Gd	3.18	100	98 Years
^{238}U	4.15	25	4.51×10^9 Years
	4.20	75	
^{235}U	4.37	18	7.1×10^8 Years
	4.40	57	
	4.58	8	
^{234}U	4.717	28	2.35×10^5 Years
	4.763	72	
^{230}Th	4.617	24	7.7×10^4 Years
	4.684	76	
^{239}Pu	5.102	12	2.44×10^4 Years
	5.143	15	
	5.156	73	
^{210}Po	5.305	100	138.4 Days
^{241}Am	5.442	13	433 Years
	5.482	86	
^{238}Pu	5.456	28	87.8 Years
	5.499	72	
^{244}Cm	5.764	23	17.8 Years
	5.806	77	
^{242}Cm	6.066	26	0.44 Years
	6.110	74	
^{252}Cf	6.076	16	2.65 Years
	6.119	84	

References: Lederer, 1978; Nuclear Data, 1966–73; Kocher, 1981.

addition it has a long half-life (24,400 yr) and readily lends itself to electroplating. Another alpha emitter that is gaining acceptance as a "single" source is Am-241 with a half-life of 433 yr and an alpha energy of about 5.5 MeV.

It is good calibration practice to employ a number of radionuclides emitting alpha particles of different energies (see Table 2.4). The range of alpha particles in materials is much shorter than the range for the same energy beta particle. Thus the ionization produced in a detector by alpha particles varies considerably with alpha particle energy, and depends on entrance window thickness, air path length, etc. The short range of an alpha particle in air (1.8 to 3.4 cm for energies listed in Table 2.4) necessitates that the instrument be calibrated and used with the detector as physically close to the radiation source as possible.

This in turn makes the instrument response strongly dependent upon the source and detector size. Figure 2.6 shows a typical calibration setup employing a large area α radiation source.

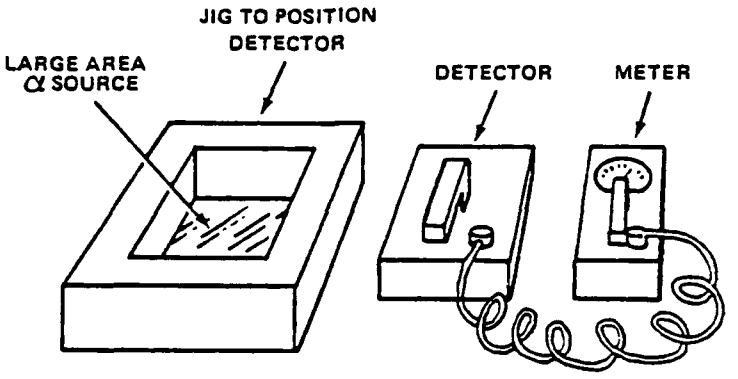

FIGURE 2.6 LARGE AREA α RADIATION CALIBRATION SETUP.

Neutron Radiation

In measuring neutron radiation, one often uses an instrument which directly measures dose equivalent. In the absence of any modifying factors, dose equivalent is the product of the quality factor, Q, and the absorbed dose at the point of interest in tissue. The quality factor relates the biological damage done by different types of radiation and depends on the linear energy transfer (LET). For photons and betas the quality factor is unity. However, for neutrons, the quality factor is a function of neutron energy and may vary between 2 and 11.

Although neutron monitoring instruments can be calibrated with neutrons produced by nuclear reactors, most neutron calibrations are made with sealed sources or accelerators. Sealed sources for calibration purposes should have conveniently long half-lives, adequate output, small physical dimensions, known neutron energy spectra, and ideally, be free from unwanted radiations. Table 2.5 lists radionuclides suitable for use in neutron instrument calibration. Anisotropy in output should be known, as should the variation of output with time. Radionuclide neutron sources are of three types: alpha-n, gamma-n, and spontaneous fission.

The alpha-n radiation sources contain an alpha emitter, such as Po-210, Pu-238, Pu-239, or Am-241 in intimate contact with a low-atomic-number element or elements, such as lithium, beryllium, boron, or fluorine, and produce neutrons distributed in energy from nearly zero to the maximum allowed by reaction kinetics. These sources can be physically small in size and are easily portable.

TABLE 2.5 SEALED RADIONUCLIDE NEUTRON SOURCES FOR INSTRUMENT CALIBRATION[1]

SOURCE	REACTION	HALF-LIFE	AVERAGE ENERGY (MeV)	APPROX. YIELD (n/sec·Ci)	APPROX. NEUTRON DOSE RATE (mrem/hr · Ci at 1 m)	COMMENT
^{124}SbBe	(γ,n)	60 Days	0.024	1.6×10^6	0.16	High intensity IER[2]
^{210}PoB	(α,n)	138 Days	2.3	6.0×10^5	0.6	
^{210}PoBe	(α,n)	138 Days	4.5	2.5×10^6	2.9	
^{226}RaBe	(α,n)	1640 Years	3.9	1.5×10^7	16.6	High intensity IER; may be yield change from ingrowth of daughters
	(γ,n)	1640 Years	0.3	1.2×10^6	0.1	
^{237}AcBe	(α,n)	21.8 Years	4.6	$\sim 1.2 \times 10^6$	1.4	Not generally available.
^{228}ThBe	(α,n)	1.9 Years	0.8	$\sim 2.5 \times 10^6$	2.3	Not generally available, high intensity IER
^{238}PuBe	(α,n)	87.8 Years	4.5	1.8×10^6	2.1	May have impurities
^{239}PuBe	(α,n)	24,400 Years	4.5	1.5×10^6	1.8	May have impurities and yield change from ^{241}Am ingrowth
^{241}AmBe	(α,n)	458 Years	4.4	2.2×10^6	2.6	Also 0.6 SF n/sec–g of ^{241}Am
^{240}Pu	SF	6600 Years	FISSION	3500	3.7×10^{-3}	Expensive
^{244}Cm	SF	18.4 Years	FISSION	1.5×10^5	0.2	Expensive, high intensity IER
^{252}Cf	SF	2.65 Years	FISSION	4.3×10^9	4.6×10^3	Expensive, high yield, useful point source, high intensity IER

(1) From Kathren, 1975.

(2) Ionizing Electromagnetic Radiation.

They can be fabricated with neutron yields up to the 10^6 - 10^8 neutron per second range, and have relatively low-intensity accompanying photon emission. Recommended alpha-n radiation sources are based on Pu-238, and Am-241. Pu-239 is also an attractive source but its use may be complicated by an ingrowth problem (ICRU 10b, 1964).

The gamma-n radiation sources consist of a gamma emitter of suitably high photon energy, such as Sb-124 or Ra-226, placed in close proximity to a low-atomic-number element, usually deuterium or beryllium. Reacting gamma rays produce neutrons by photonuclear reactions. Since most of the photons produce no neutrons, these sources also have intense photon fields. This may create personnel exposure problems, as well as interference with instrument response. Each gamma photon produces a unique energy neutron. For Ra the spectrum of gamma photons results in a spectrum of neutron energies. For Sb, most of the neutrons above the gamma-n threshold in Be are at a single energy. This results in about 95% of the neutrons having an energy of 23 keV (Harrison, 1978). The short half-life of Sb-124 (60 days) and the low neutron energy are important considerations for the use of this type source. Ra-226 gamma-n radiation sources are more generally useful, are physically small in size, and can be obtained with neutron yields up to the 10^8-10^9 neutron per second range.

Spontaneous fission neutrons, emitted in one branch of the decay of Cf-252, have a fission-type neutron spectrum in the energy range from approximately thermal to 15 MeV. These sources can closely approximate an idealized point source, can be obtained in a wide range of source strengths, i.e. to 10^6 - 10^{11} neutrons per second, and have a known spectrum of accompanying photons (ICRU 26, 1977). The relatively short half-life (2.65 yr) is a limitation to long-term use.

Radionuclide neutron sources can be sent to the National Bureau of Standards for calibration in terms of emission rate. When this is not possible, the neutron source emission rate can be determined by the long counter or manganese bath technique. On the other hand, since particle accelerators and nuclear reactors cannot be sent out for calibration, they must be standardized for instrument calibration by use of standard neutron instruments or techniques. In addition, the neutron output of these facilities must be monitored continuously during instrument calibrations. Standard neutron instruments and techniques include the precision long counter, associated particle counters (for certain reactions with certain accelerators), nuclear emulsions, fission foils, activation foils, and the manganese sulfate bath. A more detailed description of calibration and characteristics of neutron sources may be found in ICRU 10b (1964), ICRU 13 (1969), and ICRU 26 (1977).

The most widely used method for calibrating neutron sources for emission rate is with a manganese bath. This method depends on having a calibrated neutron source and making relative measurements. The source is placed at the center of a large, often spherical, tank which contains a saturated solution of $MnSO_4$. The solution acts as a

moderator and the slow neutrons produced are captured by the stable Mn-55 to give Mn-56 which decays with a half-life of 2.578 hr. The dimensions of the bath are chosen so that the escape of neutrons from the bath is kept as low as possible. Samples of the solution are measured and an absolute determination of the Mn-56 activity is made. This requires knowing the absolute efficiency for gamma rays from Mn-56 for the detectors used for this measurement. The detectors most commonly used are NaI crystals. A larger number of corrections have to be made in the estimation of the source emission rates. Neutrons may undergo fast reactions in the sulphur and oxygen if their energies are above the thresholds for these reactions; other neutrons are scattered back from the solution and reabsorbed in the source. A number of other correction factors also have to be applied and these are discussed, along with a more detailed description of the technique, in Axton (1961), De Juren (1955), and Geiger (1959).

Particle accelerators produce intense neutron fields by the interaction of accelerated charged particles, such as protons, deuterons, or tritons, on low-atomic-number target materials such as deuterium, tritium, and lithium. Available field strengths exceed the maximum emission rates of radionuclide sources thus circumventing the difficulty with nuclide sources of calibrating instruments on their higher ranges while still maintaining reasonable source-to-detector separation. Important characteristics of these neutron fields are variable intensity up to very high values (yields in excess of 10^{12} neutrons per second in some cases), occurrence of radiation in a brief pulse, monoenergetic neutron emission for any given beam-target-detector angular relationship, and lack of portability. Neutron output is a complex function of accelerator and target parameters and may be expected to vary with time even though measured machine parameters remain constant. Therefore, neutron output must be monitored constantly during instrument calibration work, and standard instruments or techniques must be used to establish neutron field values. The neutron fluence can be determined with a long counter. The efficiency of the long counter is energy dependent and when used with an accelerator, its efficiency can be determined with a Cf-252 source of known emission rate. For more details, see the use of a long counter in Section 2.4.5 and particularly Table 2.13.

2.4.4 Types of Sources and Reference Instruments

This section will present a brief overview of the relationship between the various classes of instruments discussed in this document and the calibration techniques of Section 2.4.1. The tables which follow are merely intended to be a guide with more detailed information given in the appropriate chapter. For any particular calibration method given in the tables, a different calibration method may be more appropriate for a given application of an instrument.

CALIBRATION - AN OVERVIEW

Before listing the common calibration methods for the various instrument classes, it will be useful to summarize the types of radiation commonly measured by the various instrument classes. The common types of radiation measured by instrument class are indicated in Table 2.6. A numerical code is used in Table 2.6 to indicate the likelihood that a given class of instrument will be used for the measurement of a particular type of ionizing radiation. This code is: 1) frenquently, 2) infrequently, and 3) almost never.

TABLE 2.6 TYPES OF RADIATION COMMONLY MEASURED BY VARIOUS INSTRUMENT CLASSES.

RADIATION	ION. CHAMBER	PROP. COUNTER	GM COUNTER	SCINTILLATOR	SEMICONDUCTOR	TLD	FILM	ACTIVATION FOIL	CHEM. DOSIMETER	CALORIMETER	CERENKOV
x	1	2	1	1	1	1	1	3	1	1	3
γ	1	2	1	1	1	1	1	2	1	1	3
β	1	1	1	1	1	1	1	3	1	2	1
α	1	1	1	1	1	3	3	3	3	3	3
n	1	1	3	1	1	1	1	1	3	2	3

Legend: 1—Frequently, 2— Infrequently, 3 — Almost Never

Table 2.7 summarizes the common radiation sources for the "known field" technique for calibration of the various classes of instruments. If the output of a machine is calibrated with a reference instrument and then monitored with a suitable instrument, it can then be considered to be a "known field." Only the "substitution method" of the "reference instrument" technique is considered, since in the "simultaneous method" the output from the machine does not need to be known because both the reference instrument and instrument to be calibrated are in the same field at the same time.

Table 2.8 lists the types of instruments employed in the "reference instrument" technique and the types of radiation with which they are commonly used. There is not a complete overlap with Table 2.6 since, in practice, reference instruments are not commonly used with all the types of radiation for which a given class is suitable for measuring. Also, not all instruments listed may be suitable if very accurate results are desired, i.e., what may be suitable as a reference instrument for a 10% calibration may not be suitable for a 3% calibration.

The "pseudo-reference" technique discussed in the section on calibration wells can be extended to any case in which one is

calibrating a large number of the same model of instrument, by selecting one of these for calibration in free space, and then using it as a "reference" instrument in some particular configuration and comparing other instruments of the same model against it. This is designated as "Type" in Table 2.8.

TABLE 2.7 RADIATION SOURCE TYPES COMMONLY USED WHEN CALIBRATING INSTRUMENTS WITH THE KNOWN FIELD TECHNIQUE.

RADIONUCLIDE SOURCE	ION CHAMBER	PROP. COUNTER	GM COUNTER	SCINTILLATOR	SEMICONDUCTOR	TLD	FILM	ACTIVATION FOIL	CHEM. DOSIMETER	CALORIMETER	CERENKOV
γ (^{137}Cs, ^{60}Co, ^{226}Ra) EXPOSURE	1	2	1	1	1	1	1	3	1	3	3
β (^{3}H, ^{14}C, ^{85}Kr) ACTIVITY, ABSORBED DOSE	1	1	1	1	1	1	1	3	1	3	1
α (^{239}Pu, ^{nat}U, ^{241}Am) ACTIVITY	1	1	1	1	1	3	3	3	3	3	3
n (γ, n; α, n; S.F.) EMISSION RATE	1	1	3	1	1	1	1	1	3	3	3
MACHINE SOURCE (*)											
x RAYS (X-RAY GENERATOR)	1	2	1	1	1	1	1	3	1	2	3
γ (VAN De GRAAFF, LINAC)	1	2	1	1	1	1	1	3	1	2	3
e (VAN De GRAAFF, LINAC)	1	2	1	1	1	1	1	3	1	1	1
α (VAN De GRAAFF, CYCLOTRON)	1	1	1	1	1	3	3	3	3	3	3
n (d, T GEN., VAN De GRAAFF, LINAC, CYCLOTRON)	1	1	3	1	1	1	1	1	3	3	3

(*) For fields from machines with monitors calibrated against reference instruments thereby giving fields known in terms of calibrated monitor output.

Legend: 1—Frequently, 2—Infrequently, 3—Almost Never

2.4.5 Instrument Calibration Techniques

Instruments can be classified into two use categories: those used mainly to make measurements in the field, and those used mainly to make measurements in a laboratory. Each of these two categories could be further classified into instruments measuring dosimetric quantities, and those measuring radioactivity. Examples of typical instruments in these four categories are:

Field - Dosimetry: Survey instruments measuring exposure.

Field - Radioactivity: Alpha Contamination Meter.

Laboratory - Dosimetry: Reference ionization chamber measuring exposure.

Laboratory - Radioactivity: $4\pi\beta\gamma$ ionization chamber.

TABLE 2.8 REFERENCE INSTRUMENTS COMMONLY USED WHEN CALIBRATING INSTRUMENTS WITH THE REFERENCE INSTRUMENT TECHNIQUE

REFERENCE INSTRUMENT	RADIATION TYPE				
	γ	x	β or e	α	n
ION CHAMBER EXPOSURE, ABSORBED DOSE	1	1	2	3	1
EXTRAPOLATION CHAMBER ABSORBED DOSE	3	2	1	3	3
RE-ENTRANT TYPE ION CHAMBER ACTIVITY	1	1	1	2	3
4 $\pi\beta$ PROPORTIONAL COUNTER ACTIVITY	1	1	1	3	3
CALORIMETER ABSORBED DOSE	1	1	1	3	3
TLD (EXPOSURE, ABSORBED DOSE)	1	1	1	3	1
FILM (EXPOSURE, ABSORBED DOSE)	1	1	1	3	1
CHEMICAL DOSIMETER (EXPOSURE, ABSORBED DOSE)	1	1	1	3	3
LONG COUNTER NEUTRON FLUENCE	3	3	3	3	1
NEUTRON ACTIVATION FOIL	3	3	3	3	1
"TYPE" *	1	1	1	1	1
GM COUNTER (RARELY USED AS REFERENCE INSTRUMENT.)					
SCINTILLATION DET. (RARELY USED AS REFERENCE INSTRUMENT.)					
SEMICONDUCTOR DET. (RARELY USED AS REFERENCE INSTRUMENT.)					

* See text for discussion.

Legend: 1 – Frequently, 2 – Infrequently, 3 – Almost Never

This section will focus mainly on calibration of instruments (both field and laboratory) for making dosimetric measurements and will include some discussion on calibration of field instruments for measuring (or detecting) radioactivity of samples. It will not cover calibration of laboratory instruments used to measure radioactivity. This last topic is as broad in scope and is covered very well in a NCRP Report (NCRP 58, 1958).

As seen in Section 2.4.1, there are two basic techniques for calibrating instruments: in a known field or against a reference instrument. Both of these techniques imply that at a given time and at a given point in space, the value of the radiation field in which the instrument to be calibrated is placed is known or can be

calculated. In the following sub-sections the method of determining the value of the reference field at a given time and point will be given explicitly for both the "known field" and "reference instrument" techniques.

Once one knows the value of the reference field at a particular point in space and at a particular time, one can place any type of instrument at that point and compare its observed reading against the reference value. The correction factor (CF) for the instrument being calibrated will be just the ratio of the reference value to the observed value,

$$CF = \text{reference value/observed instrument reading} \qquad (2.1)$$

If the units associated with the reference field value are not the same as the instrument being calibrated, this is a conversion factor rather than a simple scale correction factor. Since it does not make any difference what type of instrument is being calibrated in the reference field, the general principles of performing calibrations will be covered in this chapter, while any specific fine points of calibrations for a particular type of instrument will be covered in the chapter for that instrument.

Correction Factors for Determining the Reference Field

When instruments and sources are calibrated, it is for a specific set of conditions. If the conditions are different when these instruments and sources are used, it will be necessary to correct for each perturbing factor by applying an appropriate correction factor, N, to match the calibration conditions. This applies to all instruments in the calibration hierarchy given in Table 2.1. It is necessary for personnel using an instrument at one level in the hierarchy to correct the observed instrument reading so that it corresponds to the conditions at the time it was calibrated by personnel at the next higher level in the hierarchy.

Let $f_R(t_o,r_o)$ be the correction factor for either a reference instrument of calibrated source output at a unit distance as determined by a laboratory in one level of the hierarchy. Then for the reference instrument technique, the reference field, $F_R(t,r)$, at time t, and distance r, at a calibration laboratory in the next lower level of the hierarchy is

$$F_R(t,r) = f_R(t_o,r_o)\, R_{obs} \prod N_i \qquad (2.2a)$$

where R_{obs} is the observed reading of the reference instrument and $\prod N_i$ is the product of all the correction factors for pertubations. The corresponding relationship from the known field of a radioactive source is:

$$F_R(t,r) = \frac{f_R(t_o,r_o)}{r^2} \prod N_i \qquad (2.2b)$$

In addition to applying correction factors to determine the reference field at the calibration laboratory, it may also be necessary to apply correction factors to the observed readings of the instrument being calibrated, M_{obs}, to relate its reading to a specified set of conditions, M_{ref}.

$$M_{ref} = M_{obs} \prod N_i \qquad (2.3)$$

In the material which follows, the correction factors for various perturbing factors will be considered for both calibration techniques. In actual practice some of the correction factors may be sufficiently close to unity so that they need not be applied to achieve the desired level of accuracy in the calibration.

Reference Instrument Technique

Reference Instrument Conversion (or Correction) Factor: The reference chamber should be calibrated at NBS or at one of the Secondary Standards Laboratories discussed in Section 2.2. The conversion factor will be for a specific radiation characterized by some energy related parameter(s), e.g., beam energy, half-value layer, machine constant potential, etc.; and a particular value of the radiation field. The conversion factor for the reference chamber will be designated as N_R. Ignoring all other corrections, the exposure rate of the reference field, $\dot{X}_R$, will be

$$\dot{X}_R = N_R \left(\frac{R_{obs}}{t}\right) \qquad (2.4)$$

where R_{obs} is the observed integrated response of the reference instrument for time t. This is analogous to Equation 2.2a with $F_R(t,r) = \dot{X}$, $f_R(t_o,r_o) = N_R$ and R_{obs} replaced by R_{obs}/t. Note: In this chapter, a dot over a variable indicates the time rate of the variable, e.g., $\dot{x} = x/t$ = exposure rate.

1) Pressure - temperature correction: This correction must be made for all gas filled chambers which are vented to the atmosphere and is necessary because for a given chamber volume, the density of air (and thus the mass of air within the given volume) will change with pressure and temperature. The calibration report for the reference instrument will state at what temperature, in °C, and pressure (P_R and T_R) the calibration factor was determined. If the pressure and temperature in the laboratory at the time the reference

instrument is used are P_L and T_L respectively, the calibration factor for the reference instrument must be multiplied by the correction factor N_{PT} where

$$N_{PT} = \frac{(273.2 + T_L)}{(273.2 + T_R)} \frac{P_R}{P_L} \qquad (2.5)$$

The reference temperature is usually one of the following: 0, 20 or 22°C. The reference pressure is almost always 760 mm of Hg (=29.921 inches of Hg = 101.325 kPa = 1013.25 mbars).

2) Energy dependence: Most reference chambers exhibit some energy dependence. If the conditions at the calibration laboratory do not exactly match those of the laboratory calibrating the reference instrument, an explicit correction , N_E, should be made. This can best be done by having the laboratory calibrating the reference instrument calibrate it at energies above and below those used in the calibration laboratory and interpolating to the calibration laboratory conditions.

3) Saturation current: This correction applies to reference ionization chambers used in the current (as opposed to pulse) mode. The current from the ionization chamber depends on the voltage at which the ionization chamber is operated and on the value of the radiation field in which the chamber is placed (Boag, 1966). These values should be stated on the calibration report of the reference ionization chamber. If the chamber is to be used at either a lower voltage or in a more intense field, the chamber should be checked to determine if all the ion current is being collected. This can be done by placing the ionization chamber in a constant field and measuring the observed current as a function of applied voltage. For continuous radiation fields, the inverse of the ion current is proportional to the inverse square of the applied voltage. A fit of these values (Figure 2.7) will give the inverse of the saturation current, i_o.

For pulsed radiation fields, the ion current is more nearly proportional to the inverse of the voltage. Boag has described a two-voltage analysis for determining the collection efficiency for this case (Boag, 1980).

Let N_S be the correction factor for lack of complete ion current collection.

4) Electrometer corrections: In most cases the output from the reference chamber is measured by a separate instrument. Current output from a reference chamber is usually measured with an electrometer. The electrometer can be operated in either a "current" mode (e.g., measuring exposure rate) or in a "charge" mode (e.g., measuring total exposure). In either case the linearity of a particular range should be checked and a correction factor for each range should be determined. Both the current and charge mode can be checked with an appropriate combination of precision current sources, standard capacitors, precision voltage sources and accurate

timers. Let N_L be a correction factor for the scale linearity and N_{ER} be a correction factor for the electrometer range.

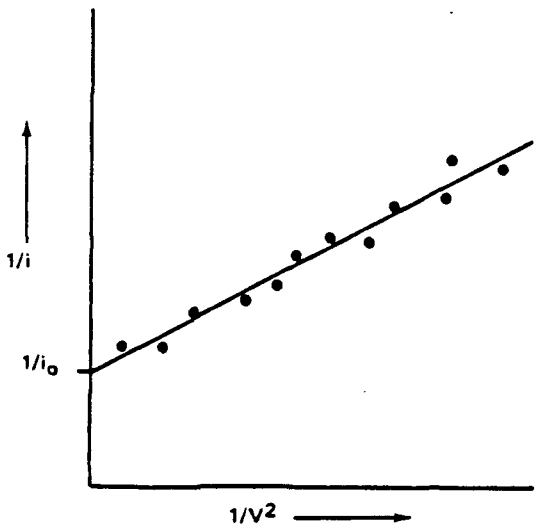

FIGURE 2.7 PLOT OF OBSERVED ION CURRENT VERSUS APPLIED VOLTAGE TO DETERMINE THE SATURATION CURRENT.

5) Dead time correction: If the pulse output from the reference chamber is recorded on a counting system, corrections will have to be made for pulses separated by less than the resolving time of the system. This can be done with pulsers and oscilloscopes or with radioactive sources (see NCRP Report 58).

6) Leakage current: When measuring small currents any leakage of charge should be accounted for. This charge leakage could be associated with the reference chamber or the electrometer and both should be checked. The leakage current will change when the voltage to the reference chamber is changed so the leakage current should be measured each time the voltage is applied to the reference chamber if it is known that this current could cause unacceptable errors in the final reading. It is possible for leakage current to increase due to the presence of radiation. This should be checked for by measuring the leakage current immediately before and after the radiation field has been removed. It will be assumed that the electrometer leakage current is negligible and that the measured leakage current from the reference instrument includes ionization due to naturally occurring radiation. The correction factor due to this will be N_{BKG}.

7) Conversion from exposure to absorbed dose: If the reference instrument is calibrated in terms of exposure and an accurate measure of absorbed dose to either air or tissue at some depth is desired, it will be necessary to make many additional corrections. These corrections are necessary for instruments used for radiation therapy but are unnecessary for instruments used for

radiation protection when the approximation that the exposure (in R) equals the absorbed dose (in rads) equals the dose equivalent (in rem). For further information on accurate absorbed dose measurements see Johns and Cunningham (1974), ICRU 14 (1969), ICRU 17 (1970), ICRU 21 (1974), ICRU 23 (1973), ICRU 24 (1976), and NCRP 69 (1981).

Known Field Technique

Source Output Conversion Factor: The output of a radioactive source can be reported in several different ways:

Exposure rate at a given distace, $\dot{X}_o$
Activity, A
Emission rate (source strength), $\dot{S}_o$
Kerma rate, $\dot{K}_o$
Absorbed dose rate, $\dot{D}_o$
Fluence rate, $\dot{\Phi}_o$
Dose equivalent rate, $\dot{H}_o$

For the simple case where no corrections are necessary, the field at a distance r from the source for these various source output characterization is:

$$\dot{\Phi} = \frac{(\dot{S}_o/4\pi)}{r^2} \qquad (2.6a)$$

where $\dot{S}_o$ is the emission rate (or source strength) into 4π steradians.

$$\dot{X} = \frac{(\dot{X}_o r_o^2)}{r^2} \qquad (2.6b)$$

The reference point, r_o, is often taken to be at unit distance.

The exposure rate can also be expressed in terms of source strength, $\dot{S}_o$, for a particular energy photon, and activity, A. Let f_i be the fraction of decays resulting in the emission of a gamma ray with energy E_i. Then

$$A = \dot{S}_o/f_i$$

and

$$\dot{X} = \frac{A}{r^2} \frac{e}{4\pi W} \sum E_i \left(\frac{\mu_{en}}{\rho}\right)_i f_i$$

where μ_{en}/ρ is the mass energy absorption coefficient in air at E_i, and W/e is the average energy to produce an ion pair in air per electric charge (33.85 J/C = 33.85 eV/ion pair, ICRU 31, 1979). The term in the bracket is the conversion factor from activity to exposure rate, i.e., the exposure rate constant

$$\dot{X} = \frac{(\Gamma A)}{r^2} \qquad (2.6c)$$

In a similar way

Absorbed dose rate: $$\dot{D} = \frac{C_D A}{r^2} \qquad (2.6d)$$

Kerma rate: $$\dot{K} = \frac{C_K A}{r^2} \qquad (2.6e)$$

Dose equivalent rate: $$\dot{H} = \frac{C_H A}{r^2} \qquad (2.6f)$$

where C represents the conversion factor from activity to the desired dosimetric quantity. Let N_{SO} represent the appropriate expression for source output characterization, i.e., the expression in parentheses in Equation 2.6. This equation is then analogous to Equation 2.2b with $F_R(t,r) = \dot{\Phi}$, $\dot{X}$, $\dot{D}$, $\dot{K}$, or $\dot{H}$, and $f_R(t_o, r_o) = N_{SO}$.

1) Source decay: All sources must be corrected for decay since the time they were calibrated. The correction factor for source decay, N_D, is

$$N_D = e^{-\lambda t} \qquad (2.7)$$

where t is the time since calibration, and the decay constant (λ) is related to the half-life ($T_{1/2}$) given in Tables 2.1 - 2.4 by

$$\lambda = \frac{\ln 2}{T_{1/2}} \qquad (2.3)$$

To determine the decay correction, $T_{1/2}$ and t should be in the same time units, i.e., both in seconds, or both in years, etc.

2) Source attenuation: There are two source attenuation corrections which may have to be applied depending on how the source was calibrated. These are corrections for attenuation within the source itself and attenuation within the source encapsulation. If

the source output is reported in terms of exposure rate at some distance, these factors have been included in the measurement of the output and no correction is necessary. If the source calibration measured the source output in the same way as above and then used some exposure rate constant (not necessarily those in Table 2.2) to convert to a source activity, again no correction is needed. In this case one should use the same value of the exposure rate constant as the source manufacturer and not the current best value listed in Table 2.2. If the source output is truly activity, then it will be necessary to make a correction for attenuation within the source and its encapsulation. The correction factor for attenuation in a thickness t, and density ρ, N_{SC}, is

$$N_{SC} = e^{-(\frac{\mu}{\rho})_c (\rho t)_c} \tag{2.9}$$

where c refers to the capsule material. For gamma rays μ/ρ can be taken to be the total attenuation coefficient (Hubbell, 1969) and for neutrons

$$(\frac{\mu}{\rho})_c = \frac{N_o \sigma_c}{M_A} \tag{2.10}$$

where N_o = Avogadro's constant (6.022×10^{23}), and σ_c = total neutron cross section (see ICRU 26, 1977; BNL-325; Schwartz, 1974) of the encapsulation material, and M_A is the molar mass. If the encapsulation is so thick that multiple scattering results in some of the radiation originally scattered out of the direction of the detector rescattering into the direction of the detector, it is necessary to multiply the value of N_{SC} by a suitable buildup factor (Rockwell, 1956; Goldstein, 1959).

The situation for source attenuation is more complicated since the decay can occur anywhere in the source and the radiation can travel in any direction. This means that one will have to choose some representative distance, $\bar{x}$, as typical of the radiation pathlength in the source. Then the correction factor for attenuation within the source itself, N_{SS}, is

$$N_{SS} = e^{-(\frac{\mu}{\rho})_s (\rho \bar{x})_s} \tag{2.11}$$

where s refers to the source material. For thick sources it may also be necessary to include a buildup factor. The selection of $\bar{x}$ becomes more critical as source dimensions increase since some of the radiation may become completely absorbed within the source.

If there is a spectrum of radiation from the source, the

correction factors should be averaged over the spectrum of the radiation.

If the source output is given in terms of emission rate, the necessity of including source attenuation corrections will depend on how the emission rate was measured and reported on the calibration certificate.

3) Air attenuation: The basic form of the air attenuation correction factor, N_A, is

$$N_A = e^{-(\frac{\mu}{\rho})_a (\rho r)_a} \qquad (2.12)$$

The attenuation coefficient for air, $(\mu/\rho)_a$, is determined in the same manner as for source encapsulation.

The total attenuation coefficients for photons in air are given in Table 2.9 (Hubbell, 1982):

TABLE 2.9 TOTAL ATTENUATION COEFFICIENT FOR AIR

E(MeV)	μ/ρ(cm^2/g)
0.661 (Cs)	0.07715
0.800 (Ra)	0.07074
1.25 (Co)	0.05681

The density of air relative to STP is

$$\rho = 0.001293 \frac{273.2}{(273.2 + T)} (\frac{P}{760}) \frac{g}{cm^3} \qquad (2.13)$$

where P is the pressure (in mm Hg) at the time the source is used and T is the corresponding air temperature (in ^{o}C). Note that this density correction is just the inverse of N_{PT} since N_{PT} applies to exposure or dose which has the air mass, or density, in the denominator.

If a finite air path is part of the measurement determining the source output, then r represents the distance from the calibration point to the effective center of the detector, otherwise it is the distance from the edge of the source to the edge of the detector.

4) Source anisotropy: The emission rate from a source may not be isotropic due to non-spherical source construction and difference between in-scatter and out-scatter in the source encapsulation. This can be either measured, or in some cases calculated. Designate this correction factor by N_{NI}.

Both Techniques

1) Timing end-errors: Due to the way an x-ray shutter operates or the way a source is positioned, the actual irradiation time may not correspond to the preset time interval. This timing end-error can be determined as follows (see NCRP Report 69). Make a long exposure for time t_1 and let the corresponding meter reading be M_1. Divide the interval t into n shorter segments. Make n exposures of total time $t_2 = (t_1/n)$ and let the total reading for these n exposures be M_2. Then the timing error has occurred once in the reading M_1 and n times in the reading M_2. Let Δt be the timing error where

$$\Delta t = \frac{M_2 t_1 - M_1 t_2}{n M_1 - M_2} \qquad (2.14)$$

If Δt is positive, the actual irradiation time is found by adding Δt to the preset time, whereas if Δt is negative the actual irradiation time is found by subtracting Δt from the preset time. Let the correction factor due to timing end-errors be N_T.

TABLE 2.10 NET INCREASE IN RESPONSE DUE TO NEUTRONS SCATTERING IN AIR.

	INCREASE PER METER (IPM)	
	BARE ^{252}Cf	MODERATED ^{252}Cf
	(%)	(%)
FLUENCE	1.2	4.0
DOSE EQUIVALENT	1.0	1.5
NTA FILM, POLYCARBONATE TRACK ETCH DOSEMETER	0.5	0.9
9" SPHERICAL REMMETER	1.0	2.3
ALBEDO DOSEMETER	1.1	3.0
3" SPHERE	1.7	4.5

2) Air scatter: If the air path is sufficiently great that multiple scattering can occur, it is necessary to multiply N_A by a buildup factor (or its equivalent). For reasonable path lengths the buildup factor for x and gamma rays for air is taken to be unity. For neutrons, scatter by air is more important than absorption by air. Source neutrons travelling directly toward the detector can be scattered so that they never reach the detector (out-scatter) and conversely, source neutrons not travelling toward the detector can be scattered into the detector (in-scatter). Let $N_A N_{AS}$ denote the difference between in-scattered and out-scattered neutrons. This difference has been calculated (Schwartz and Eisenhauer, 1982) for a few selected cases for neutrons from bare ^{252}Cf and ^{252}Cf in a D_2O sphere. The results are reported in percent increase per meter in in-scattering over out-scattering. This means that (detector)

response should be decreased by the percentages given in Table 2.10 to obtain the free field responses, i.e., $N_A N_{AS} = 1-(IPM/100)r$ where r is the source-detector distance.

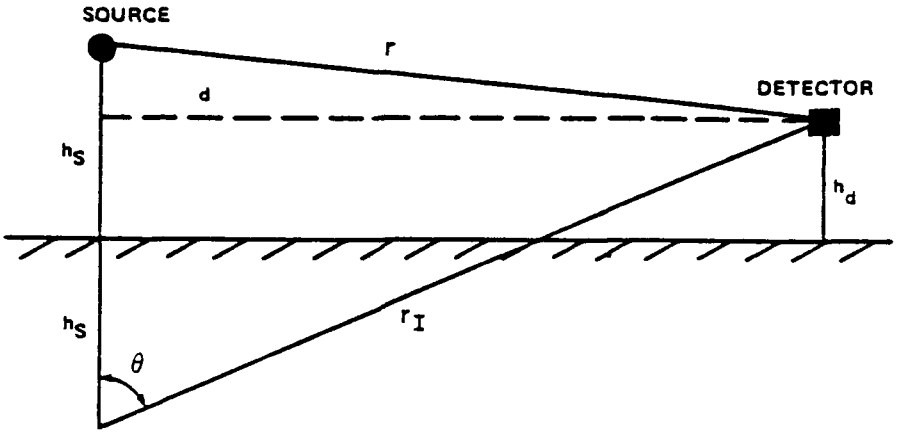

FIGURE 2.8 COORDINATES FOR CALCULATING SINGLE SURFACE RETURN.

3) Room return: Radiation can be scattered from large area surfaces such as floors into detectors. In an analogy to electrostatic electricity, Eisenhauer (1965) has developed an image source technique for calculating reflections of both gamma rays and neutrons from a single surface. The geometry is shown in Figure 2.8. Here r is the source to detector distance, r_I is the distance from the image source to the detector, h_s and h_d are the distances of the source and detector from the reflecting surface and d is the perpendicular distance between the source-image source line and detector. Let F_s and F_d respectively be the field due to the reflected (scattered) radiation and direct radiation, then

$$F_s/F_d = (\frac{r}{r_I})^2 \, R(\Theta, \frac{h_d}{h_s}) \qquad (2.15)$$

where the reflection coefficient R (which is a function of θ and h_d/h_s) for a ^{60}Co gamma photon scattering from concrete has been calculated by Monte Carlo techniques and is plotted in the reference. The reflection coefficient increases rapidly from about 0.03 for $\cos\theta = 0$ to a maximum of 0.12 at $\cos\theta = 0.22$ and slowly decreases to 0.08 at $\cos\theta =$ ... Experimental data on the reflection coefficient are given for fast neutrons scattering from water and concrete and calculations are made for several types of one-velocity scatter. Schwartz and Eisenhauer (1982) expressed Equation 2.15 as

$$F_s/F_d = 2\alpha g(\frac{\sigma_r}{\sigma})(\frac{r}{r_I})^2 \cos\Theta \qquad (2.16)$$

where α is the albedo of the reflecting surface (0.54 for epicadmium neutrons for concrete decreasing by about 20% for saturated soil), g is a factor to account for anisotropic detector response, σ_r and σ the spectrum averaged response for the reflected and direct neutrons respectively, $\theta = \tan^{-1} d/(h_s + h_d)$, and $r^2_I = (h_s + h_d)^2 + d^2$.

Values of $g(\sigma_r/\sigma)$ for a bare and moderated Cf source are given (Schwartz and Eisenhauer, 1982) in Table 2.11.

TABLE 2.11 CALCULATED VALUES OF THE FACTOR $g(\sigma_r/\sigma)$ FOR SINGLE SURFACE REFLECTION.

	BARE ^{252}Cf	MODERATED ^{252}Cf
FLUENCE	1.0	1.0
DOSE EQUIVALENT	0.37	0.6
NTA FILM, POLYCARBONATE TRACK ETCH DOSEMETER	0.2	0.3
9" SPHERICAL REMMETER	0.68	0.75
ALBEDO DOSEMETER	1.0	0.6
3" SPHERE	1.8	1.1

In an enclosed concrete room, each neutron makes abut 2 1/2 traversals before being captured. These room-scattered neutrons are essentially uniformly distributed throughout the room. In analogy to Equation 2.16, the ratio of instrument response to reflected and direct radiation for a bare Cf-252 source in a concrete room with $r << h$, is

$$F_s/F_d = 5.6\ g\ (\frac{\sigma_r}{\sigma})(\frac{r}{r_c})^2 \qquad (2.17)$$

with $4\pi r^2_c = \Sigma A_i$ where A_i is the area of the ith surface of the room and the summation is over the six room surfaces.

The reference field at the calibration point due to both direct and scattered components is

$$F_R(t,r) = \frac{f_R(t_o,r_o)}{r^2} + F_s$$

Combining this equation and Equation 2.17

$$F_R(t,r) = \frac{(1 + Sr^2)f_R(t_o,r_o)}{r^2} \qquad (2.18)$$

where $S = 5.6g(\sigma_r/\sigma_o)(4\pi/\Sigma A_i)$. The room return correction

factor is

$$N_{RR} = (1 + Sr^2) \tag{2.19}$$

If the room return correction factor is applied to the instrument reading rather than to the reference field, the reciprocal of Equation 2.19 should be used. For those cases where $g(\sigma_r/\sigma)$ is not known, S can be determined from the slope of the line obtained by plotting $M_{obs}\ r^2$ vs r^2 for various r.

For scattering from a single surface, Jenkins (1980) has used the Monte Carlo code MORSE to study neutrons from a PuBe source reflected from concrete and gives formulae which do not explicitly contain the albedo of the reflecting surface, and which fitted the scattered component to within 30%. The expression for fluence is

$$\Phi = \frac{S_o}{4\pi r^2}\ 1 + \frac{1.52\ (r_I/r)}{(1 + 0.1E)(1 + (r_I/r)^3)} \tag{2.20}$$

where S_o is the source emission, E is the neutron energy in MeV, and r_I is the same as in Equation 2.17. The expression for dose equivalent is

$$H = \frac{S_o C_\Phi}{4\pi r^2}\ 1 + \frac{0.75\ (r_I/r)}{1 + (r_I/r)^3} \tag{2.21}$$

where C_Φ is the spectrum averaged conversion factor from fluence to dose equivalent.

McCall (1978, 1979) has also used the computer code MORSE to calculate the scattered component of accelerator produced neutrons in concrete rooms. He found the scattered neutrons were constant in the room and that the scattered neutron fluence was given by

$$\Phi_s = k_1 \frac{S_o}{S} \tag{2.22}$$

where S_o is the fast neutron source strength and S is the area of the room. The constant k_1 depends on the energy of the neutron spectrum and was 4.6 for tungsten-shielded medical linear accelerators and 5.4 for lead-shielded medical linear accelerators. For fluence measuring instruments $S_o = 4\pi r^2\ \Phi_o$ and $g(\sigma_r/\sigma) = 1$, so Equations 2.17 and 2.22 are the same providing $k_1 = 5.6$. McCall also found that the average energy of the scattered neutrons was 0.24 times the average energy of the primary neutrons.

4) Shadow shield: The corrections for air scatter and room return can be determined by the shadow-shield method. The principles are shown in Figure 2.9.

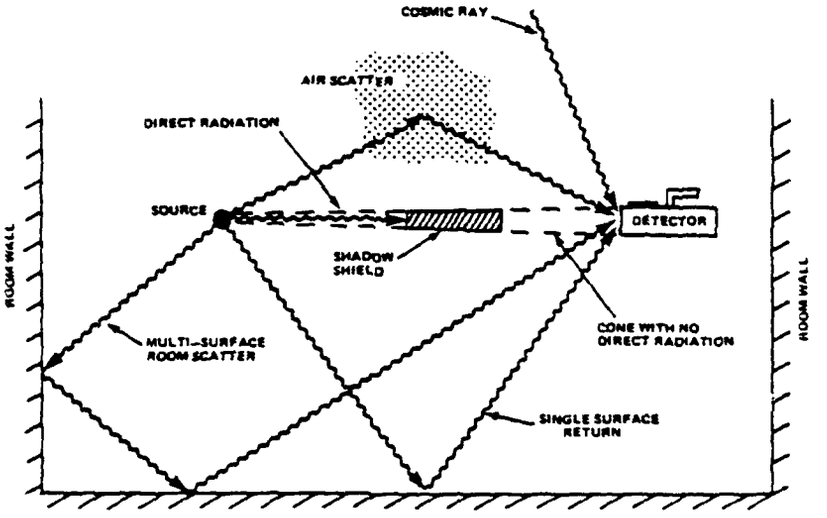

FIGURE 2.9 RADIATION REACHING DETECTOR IN SHADOW SHIELD MEASUREMENT.

First, a measurement is made with the source unexposed (or shutter closed) and no shadow shield to measure the response due to background plus leakage, R_{BKG}. *Second*, a measurement is made with the source exposed (or shutter open) which measures the response due to the source, background, leakage, room return, and air scatter. Finally, a measurement is made with the shadow shield in place to measure the response due to background, leakage, room return, and air scatter.

The shadow shield should shield just the detector from the direct response of the source and should not be so large that it significantly changes the air scatter component reading of the detector or significantly "shadows" the back wall.

The above correction factors are summarized in Table 2.12. Measurements may show that some of the corrections are near enough to unity that they do not need to be applied for the desired accuracy of the calibration.

Consider the reference instrument technique. Knowing the value of the reference field at a point in space at a particular time allows us to place the effective center of any instrument at that point and compare its response with the known value to determine the correction factor for the instrument being calibrated, i.e., the observed response of the instrument is being compared with the known value of the field existing when the instrument being calibrated is not present. In the following assume the reference field is known in terms of exposure. Let $(R_s)_c$ be the response of the instrument being calibrated (c) to the reference field. Then the correction factor will be

$$CF = \frac{\dot{X}_{Ref}}{(R_s/t)_c} \qquad (2.23)$$

where t is the time for instruments which integrate over the total exposure, or

$$CF = \frac{\dot{X}_{Ref}}{\langle \dot{R} \rangle_c} \qquad (2.24)$$

where $\langle \dot{R} \rangle_c$ is the average reading over the exposure time for those instruments which read rate.

TABLE 2.12 SUMMARY OF CORRECTION OR CONVERSION FACTORS FOR REFERENCE INSTRUMENT AND KNOWN FIELD TECHNIQUES.

TECHNIQUE	SYMBOL	CORRECTION OR CONVERSION FACTOR
REFERENCE-INSTRUMENT	N_R	CONVERSION FACTOR FOR REF. INSTRUMENT
	N_{PT}	PRESSURE-TEMPERATURE CORRECTION
	N_E	ENERGY DEPENDENCE OF REF. INSTRUMENT
	N_S	SATURATION CURRENT EFFECT
	N_{BKG}	LEAKAGE CURRENT + NATURAL BACKGROUND
	N_{DT}	DEAD TIME CORRECTION (PULSE INSTR.)
	N_L	ELECTROMETER SCALE LINEARITY
	N_{ER}	ELECTROMETER RANGE CORRECTION
	N_T	SHUTTER TIMING END-EFFECT CORRECTION
	N_{RR}	ROOM RETURN
	N_{AS}	AIR SCATTER
KNOWN FIELD	N_{SO}	SOURCE OUTPUT CONVERSION
	N_D	SOURCE DECAY
	N_{NI}	SOURCE ANISOTROPY
	N_{SA}	SOURCE ATTENUATION
	N_A	AIR ATTENUATION
	N_{AS}	AIR SCATTER
	N_{RR}	ROOM RETURN
	N_T	SHUTTER TIMING END-EFFECT CORRECTION

The observed response of the instrument being calibrated will consist of the following components

$$(R_{obs})_c = (R_{Source} + R_{\substack{Air \\ Scatter}} + R_{\substack{Room \\ Return}} + R_{Bkg} + R_{\substack{Timing\ end \\ offset}})_c$$

The response due solely to direct radiation will be

$$R_s = (R_{obs})_c \, N(c)$$

where

$$N(c) = (N_{AS} N_{RR} N_{BKG} N_T)_c \qquad (2.25)$$

and corrects for the other effects measured by the instrument being calibrated. If we want the source response referenced to some pressure and temperature, N(c) must be multiplied by $(N_{PT})_c$.

Similarly, the observed response of the reference instrument to the source will be

$$(R_{obs})_R = (R_{Source} + R_{Air\ Scatter} + R_{Room\ Return} + R_{Bkg} + R_{Timing\ offset\ end})_R$$

and the response to the direct component of the reference field will be

$$(R_s)_R = (R_{obs})_R \, N(R)$$

where

$$N(R) = (N_{AS} N_{RR} N_{BKG} N_T)_R \qquad (2.26)$$

and similarly corrects for effects measured by the reference instrument.

The value of the reference field for the reference pressure and temperature will be

$$\dot{X}_R = N_R \left(\frac{N_{DT} R_s}{t}\right)_R N(R) \, N_{ER} N_L \qquad (2.27)$$

and the overall correction factor for the instrument being calibrated is

$$CF = \frac{\text{ref. value}}{\text{obs. reading}} = N_R \frac{(R_{obs}/t)_R}{(R_{obs}/t)_c} N_{CF}^R \qquad (2.28)$$

where

$$N_{CF}^{R} = \frac{(N_{PT}N_{AS}N_{RR}N_{BKG}N_{T})_{R}}{(N_{PT}N_{AS}N_{RR}N_{BKG}N_{T})_{C}} N_{ER}N_{L}N_{E}N_{S} \qquad (2.29)$$

A correction term has been included to account for the possibility of the energy used in the calibration being different than the energy at which the reference chamber was calibrated and for saturation current effects.

For a good electrometer, $N_{L}N_{ER}$ is approximately unity, and assuming the reference instrument and test instrument are used in beams of the same energy, $N_{E} = 1$, and the terms in the ratio can be measured. To first order this ratio, N_{CF}^{R}, is unity.

Now consider the known field technique. The reference field is given by

$$\dot{\chi}_{R} = \frac{N_{SO}}{r^{2}} N(S) \qquad (2.30)$$

where

$$N(S) = N_{D}N_{SA}N_{A}N_{AS}$$

and N_{SO} represents the calibrated source output in the desired dosimetric quantity. The correction factor for the instrument being calibrated is

$$CF = \frac{\text{ref. value}}{\text{obs. reading}} = \frac{N_{SO}}{r^{2}} \left(\frac{1}{R_{obs}/t}\right)_{C} N_{CF}^{S} \qquad (2.31)$$

where

$$N_{CF}^{S} = \frac{N_{D}N_{SA}N_{A}N_{AS}}{(N_{PT}N_{RR}N_{BKG}N_{T})_{C}} \qquad (2.32)$$

This correction factor is not necessarily near unity as was the case in the reference instrument technique. The known field technique depends on knowing the value of r, whereas the reference instrument technique only requires that the effective centers of both instruments be at the same spot.

X-Ray Instrument Calibration

X-ray instruments are normally calibrated with an x-ray machine, although they can also be calibrated with an Am-241 source (60 keV). There are two types of calibrations of interest: 1)

energy response of the instrument, and 2) overall correction factor of the instrument. If one is only interested in the energy response of the instrument one normally uses fluorescence x-rays or heavily filtered x-rays (see ISO 4037), whereas if one is interested in a calibration factor one generally calibrates the instrument with a spectrum which matches the field measurement as nearly as possible.

Reference Instrument Technique

When using x-ray machines, the reference instrument technique is the most common method. In calibrating x-ray instruments it is necessary to characterize the x-ray beam in which they are calibrated. This is generally done by specifying the amount of added filter materials; the kilovoltage of the x-ray unit (preferably constant potential - less than 10% ripple (ISO 4037); the half-value layer (HVL); the homogeniety coefficient (HC), the ratio of the first HVL of Al to the second HVL of Al; or the effective energy.

If the half-value layer of an x-ray machine is measured with an energy dependent detector, it will be necessary to correct the observed readings as a function of added material since the HVL of the new beam consisting of the original added filter material plus the added material of the HVL measurement changes each time material is added. The HVL also depends on the source - detector distance since changing this distance will change the spectrum due to absorption in air.

The measured exposure rate has a power law variation with the kilovoltage of the x-ray machine, $\dot{X} = aV^n$ where n is usually between two and three. The measured exposure rate is directly proportional to the tube current, $\dot{X} = a + bI$ where a is due to dark current and possibly due to amount of ripple present when the tube current changes. To account for variations in the reference field between exposures with the reference chamber present and with an instrument to be calibrated present, a transmission monitor can be placed in the x-ray beam line.

When using a reference instrument, the dependence on the source-effective center distance, r, is small. The main concern is to ensure that the effective center of both the reference instrument and the instrument to be calibrated are at the same place. There is another r dependence, namely, beam uniformity. Let the dimension of the detector perpendicular to the x-ray beam axis be 2x. Then the fluence at the edge of the detector is reduced from that of the center of the detector by a factor of $r^2/(r^2 + x^2)$. ANSI N325 (1978) recommends that r be greater than 7 times the detector dimension. In addition to beam uniformity depending on r, there is an additional dependence on self-absorption effects of the electron beam in the anode of the x-ray tube. This is called the "heel effect." See ICRU 10b (1962) for more discussion of this effect.

Typical instruments used as reference chambers for calibrating x-ray instruments are Shonka-Wyckoff or "R Chamber" ionization chambers. The reference x-ray field, $\dot{X}_R$, measured with one of these

reference instruments per monitor count, M_R, is

$$\frac{\dot{X}_R}{M_R} = \frac{N_R}{M} \left(\frac{N_{PT} R_{obs}}{t}\right)_R N(R) \qquad (2.33)$$

where R_{OBS} is the electrometer reading, t is the preset time, M is the monitor reading with the reference instrument present, and N(R) is given by Equation 2.26.

Let $(R_{OBS})_c$ be the reading of any type of x-ray measuring instrument placed in this field (e.g., TLD, GM tube, solid state detector, etc.) and let CF be the correction factor by which we need to multiply the observed reading by to obtain the "true" reading. Then the corrected test instrument reading per monitor count must equal the reference field per monitor count, M_c, or the correction factor is

$$CF = \frac{M_c}{M_R} N_R \frac{(R_{obs}/t)_R}{(R_{obs}/t)_c} N^R_{CF} \qquad (2.34)$$

where N^R_{CF} is given by Equation 2.29.

Known Field Technique

As already mentioned the known field technique is much less common with x rays. The most common source is Am-241 which emits 60 keV gamma rays. In addition to gamma rays, there are also alpha rays which can interact with oxygen and nitrogen to produce neutrons by the (α,n) reaction. The basic principles of using an Am-241 source are the same as for a gamma source discussed in the next section.

Gamma-Ray Instrument Calibration

Both the reference instrument technique and the known field technique are commonly used to calibrate gamma-ray instruments. The most common sources are Cs-137 and Co-60, and to a lesser extent Ra. If one wants higher energy gamma rays, a common method is to use a charged particle reaction with an accelerator.

Reference Instrument Technique

The basic principles of using a reference instrument for gamma fields is essentially the same as for x-rays and the basic method can be found there. For gamma rays one usually specifies the effective energy which in this case is simply the average energy of the gamma rays. With gamma-ray sources, monitors are not normally used, but if charged particle reactions with accelerators are used, monitors should be used.

The one major difference between using a reference instrument

for x rays or gamma rays is if the gamma-ray source is in a calibration well. As seen in Section 2.4.1, calibration in a calibration well is a two step process in which for each type of instrument calibrated an instrument of that type is selsected to serve as a pseudo-reference instrument. The instrument is first calibrated in free field conditions by determining its free field correction factor, CF_{PR}, either using the known field technique or the reference instrument technique. Let $\dot{X}_R$ be the free reference field value, let $R_{PR}(F)$ be the reading of the pseudo-reference instrument in the free field, and let $N_{PT}^{PR}(F)$ be the pressure-temperature correction for the pseudo-reference instrument in the free field. The free field calibration factor is

$$CF_{PR} = \frac{\dot{X}_R}{N_{PT}^{PR}(F)R_{PR}(F)/t} \tag{2.35}$$

The pseudo-reference instrument is now placed in the calibration well and its reading is taken in the well, $R_{PR}(W)$, with a corresponding pressure-temperature correction, $N_{PT}^{PR}(W)$. Finally, the instrument being calibrated (of the same type as the pseudo-reference instrument) is placed in the well. Depending on which of the calibration adjustment procedures of Section 2.4.2 is being used, one can determine the correction factor of the instrument being calibrated in two ways. One can adjust this instrument to read the same as the pseudo-reference instrument so that the correction factor for both is the same and equal to the free field calibration. Alternatively, one can form a calibration table by comparing the pressure-temperature corrected readings of the two instruments. In this case the correction factor for the instrument being calibrated, CF_T, will be related to the free field calibration factor of the pseudo-reference instrument by

$$CF_T = CF_{PR}\frac{R_{PR}(W)}{R_T(W)}\frac{N_{PT}^{PR}(W)}{N_{PT}^{T}(W)} \tag{2.36}$$

Known Field Technique

When one thinks of sources it usually is of point sources. The case for irradiators containing gamma sources is essentially the same but one needs to correct for an additional scattering component for scattering from the surfaces of the irradiator. These corrections are usually small enough not to require the use of a pseudo-reference instrument described in the calibration well case.

As indicated in Section 2.5.1, the output of the source (reference field) can be expressed in terms of exposure rate at a

given distance, activity, or emission rate.

1) Reference field, $\dot{X}_R$, when output is measured in terms of exposure rate, $\dot{X}_o$, at a reference distance, r_o, is

$$\dot{X}_R = \frac{(\dot{X}_o r_o^2)}{r^2} N(S) \qquad (2.37a)$$

where r = distance from the effective center of the source to the effective center of the instrument being calibrated, and

$$N(S) = N_D N_A N_{SA}$$

where N_A = air attenuation past the point at which the source was calibrated. The reference distance is often taken to be at a unit distance so r_o often does not appear in this type of equation.

2) Reference field, $\dot{X}_R$, when output is expressed in terms of activity, A, is

$$\dot{X}_R = \frac{(\Gamma A)}{r^2} N(S) \qquad (2.37b)$$

where Γ is the exposure rate constant. If the source calibrator explicitly measured the exposure at some distance and then converted to an effective source activity,

$$N(S) = N_D N_A' N_{SA}$$

where N_A' = air attenuation past the point at which the source was calibrated, and if the actual activity of the source is determined

$$N(S) = N_D N_A N_{AS} N_{SA}$$

where N_A is air attenuation for entire path.

3) Reference field, $\dot{X}_R$, when output is given in terms of emission rate of photons with a particular energy. In this case it is necessary to know the decay scheme to be able to determine both the activity and exposure rate constant.

Let $(R_{OBS})_c$ be the observed reading of the test instrument placed in the reference field. The correction factor for all three cases will be the same

$$CF = \frac{\dot{X}_R}{(N_{PT} R_{obs}/t)_c N(c)} = \frac{N_{SO}}{r^2} \frac{1}{(R_{obs}/t)_c} \frac{N(S)}{N(c)} \qquad (2.38)$$

where N(c) is given by Equation 2.25, N_{SO} is the appropriate

expression for source output, and N(S) is the corresponding correction factor as discussed above.

In addition to dependence directly on r^2, there is an additional dependence on r through the non-uniformity of the beam over the detector area in the same manner as discussed for x-ray fields.

Neutron Instrument Calibration

When dealing with neutrons, it is convenient to discuss three energy ranges, thermal, moderate, and fast. The boundary between moderate and fast is not sharp as is the case for thermal neutrons.

Reference Instrument Technique

Thermal Neutrons

1) BF_3 or ^3He counter: As an example of this kind of detector consider a BF_3 counter. This counter is operated in the proportional region and detects alpha particles by the $^{10}B(n,\alpha)^7Li$ reaction. By operating in a proportional mode, good separation between the alpha particels produced by the (n,α) reaction and electrons produced by the (γ,e) reaction can be achieved.

These detectors operate in a pulse mode where the individual events are recorded separately rather than in the current mode as are the reference ionization chambers used in x-ray and gamma-ray instrument calibration. This means that a correction for dead time may be necessary, but there is no need for electrometer corrections. Since BF_3 counters are sealed chambers, no pressure-temperature correction is necessary.

The reference instrument is usually calibrated in terms of fluence (or fluence rate) incident on the detector. The fluence rate in the reference field at a particular point and time in space will be

$$\dot{\Phi}_R = N_R \left(\frac{R_{obs}}{t}\right)_R N'(R) \qquad (2.39)$$

where N'_R is the conversion factor in terms of fluence rate per detector pulse, and the correction factor N'(R) is

$$N'(R) = (N_{DT} N_{AS} N_{RR} N_{BKG} N_T)_R \qquad (2.40)$$

2) Gold foils: These can be used in two ways: either by using the constants of the thermal capture reaction on gold, or by irradiating gold foil in a known fluence, and use this to calibrate the counting system.

The activity induced in a gold foil, A, will be

$$A = n\sigma_{capt.} \times a\dot{\Phi} \qquad (2.41)$$

where n is the number of atoms/cm³ = N_o/M_A (N_o = Avogadro's constant and M_A is the molar mass, σ_{CAPT} is the gold capture cross section (98.65 ± 0.09 barns), x is the foil thickness, a is the foil area, and $\dot{\Phi}$ is the fluence rate.

For long irradiation it will be necessary to correct for decay during the irradiation. For irradiation time t, the activity at the end of irradiation, A(t), is

$$A(t) = A(1 - e^{-\lambda t}) \qquad (2.42)$$

For Au-198, $T_{1/2}$ = 2.696 days.

If one can absolutely count the activity induced in the gold foil, the fluence rate of the thermal neutron beam can be determined.

The other method of using gold foils is to irradiate them in a known fluence and then use them to calibrate the counting system. Let $C_{\Phi A}$ be the conversion factor from fluence rate to activity (=nσxa). For a gold foil with known activity, the observed count rate (corrected for dead time) in the experimental counting system using the standard is

$$\dot{C}_S = \varepsilon A_{STD} N_D^S = \varepsilon C_{\Phi A} \dot{\Phi}_{STD} N_D^S \qquad (2.43)$$

where ε is the counter efficiency, $\dot{\Phi}_{STD}$ is the fluence rate used to irradiate the standard, and N^S_D is the decay correction from the time the standard was originally irradiated to the time it was counted, i.e., $e^{-\lambda t}$. The count rate due to foil irradiation in the users reference thermal beam will be

$$\dot{C}_R = \varepsilon A_R N_D^R = \dot{C}_S \frac{N_R^D}{N_D^S} \frac{A_R}{A_S} = \dot{C}_S \frac{N_D^R}{N_D^S} \left(\frac{C_{\Phi A}}{A_S}\right) \dot{\Phi}_R \qquad (2.44)$$

and the reference field fluence rate will be

$$\dot{\Phi}_R = \frac{N_D^S}{N_D^R} \frac{\dot{C}_R}{\dot{C}_S} \frac{A_S}{C_{\Phi A}} = \frac{\dot{C}_R}{\dot{C}_S} \frac{N_D^S}{N_D^R} \dot{\Phi}_{STD} \qquad (2.45)$$

If irradiation times are long and counting times are long, explicit corrections for these effects must be made.

3) Fission Chambers: These are ionization chambers (or

proportional counters) which detect the ionization produced when the fission fragment travels through the counting gas.

Fission chambers can also be used in two modes. The simpler is to have the output calibrated in terms of a known thermal fluence. In this case the same expression for the reference field is obtained as for the BF_3 counter case (Equation 2.39). The other case is if the mass per unit area of the fission deposit material is known. This case is very similar to the gold foil case. The count rate in the fission chamber due to the reference field will be

$$\dot{C}_R = \frac{mN_0}{M_A} \langle \sigma_{fission} \rangle \, a \, \dot{\Phi}_R \qquad (2.46)$$

where m is the fission deposit mass per unit area, "a" is the area of the deposit, and $\langle \sigma_{FISSION} \rangle$ is the fission cross section averaged over the incident neutron spectrum taken to be thermal in this case.

In addition to correcting for pulses due to alpha particles naturally occurring in the fission deposits, there are a number of corrections such as self-absorption in the fission foil, scatter from the foil backing, counting efficiency, etc. which must be made (Heaton, 1975; Gilliam, 1975).

For all of these cases the correction factor for a test neutron instrument placed at the calibration point in the reference field will be

$$CF = \frac{\dot{\Phi}_R}{(R_{obs}/t)_c N'(c)} \qquad (2.47)$$

which for pulse counting field instruments is

$$N'(c) = (N_{DT} N_{AS} N_{RR} N_{BKG} N_T)_c \qquad (2.48)$$

If one is interested in dose equivalent rate instead of fluence rate one must use an appropriate conversion factor.

$$\dot{H} = C_\phi \, \dot{\Phi} \qquad (2.49)$$

For thermal neutrons

$C_\phi = 1.031 \times 10^{-9}$ rem·(n·cm^{-2})$^{-1}$ (NCRP 39, 10CRF20)

$C_\phi = 1.068 \times 10^{-9}$ rem·(n·cm^{-2})$^{-1}$ (ICRP 21)

Often the detectors described in this section are covered with cadmium. Cadmium will capture the thermal neutrons due to its large

thermal cross section, so any observed response will be due to higher energy neutrons or to background, and other radiation effects.

Moderate Energy Neutrons

4) Fission chambers: This is the same as for the thermal case except the $\langle\sigma_{FISSION}\rangle$ is over the actual neutron spectrum in the moderate energy reference beam.

5) Remmeter: These are instruments which detect neutrons that are moderated to thermal energies. Their response is tailored in an attempt to match the curve of dose equivalent dependence on energy. Their output for a given spectrum can be calibrated in terms of fluence and the expression for the reference field using such a calibrated Remmeter will be the same as Equation 2.39 and 2.47 for a BF_3 counter.

Fast Neutrons

6) Long counter: For sufficiently intense beams fission chambers could be used as reference instruments. Remmeters could also be used. For accelerator produced neutrons, the neutron fluence can be monitored with a (dePangher) long counter (dePangher, 1966).

The observed count rate, C, of the long counter, corrected for dead time, is

$$\dot{C} = \dot{C}_{scatter} + \frac{\varepsilon(\dot{S}_o/4\pi)}{(r + d_o)^2} \qquad (2.50)$$

where $\dot{C}_{SCAT}$ is the count rate due to scattered neutrons and can be measured with a shadow cone, ε is the product of the detector efficiency and the area of the long counter, $\dot{S}_o/4\pi$ is the neutron emission rate into 4π, and d_o is the distance to the effective center of the long counter. Based on data in BCS 0813, d_o can be represented by

$$d_o = (-0.26 + 0.12E + 0.05E^2) \qquad (2.51)$$

with d_o in cm and E in MeV.

When used with an accelerator, the long counter can be calibrated with a Cf-252 source of known emission rate (expressed as a known fluence rate at the surface of the detector). The count rate in the long counter due to the Cf-252 source will be

$$\dot{C}(Cf) = \dot{C}_s(Cf) + \frac{\varepsilon_{Cf}(\dot{S}_o/4\pi)}{(r + d_o)_{Cf}} Cf$$

The count rate due to the accelerator will be

$$\dot{C}(acc) = \dot{C}_s(acc) + \left(\frac{\varepsilon_{acc}}{\varepsilon_{Cf}}\right) \varepsilon_{Cf} \frac{(\dot{S}_o/4\pi)_{acc}}{(r + d_o)_{acc}}$$

so the neutron emission rate in the accelerator beam is

$$(\dot{S}_o)_{acc} = \frac{(\dot{C} - \dot{C}_s)_{acc} (r + d_o)^2_{acc}}{(\dot{C} - \dot{C}_s)_{Cf} (r + d_o)^2_{Cf}} \frac{(\dot{S}_o)_{Cf}}{\varepsilon_{ref}} \qquad (2.52)$$

where the efficiency of the long counter for the accelerator produced neutrons relative to Cf-252 is given in Table 2.13 (from BCS 0813). Note in Equation 2.52 the count rate due to scattered neutrons is not necessarily the same for the accelerator produced neutrons, and C_s should be measured in both cases with a shadow shield.

The correction factor for instruments placed in this beam will be

$$CF = \frac{\dot{\Phi}_{acc}}{(R_{obs}/t)_c N'(c)} \qquad (2.53)$$

where N'(c) is given by Equation 2.48 and the fluence rate,

$$\dot{\Phi}_{acc} = (\dot{S}_o)_{acc} [4\pi(r + d_o)^2]^{-1} \qquad (2.54)$$

Instruments such as proton telescopes, associated particle counters, etc., for determining neutron fluence rate are beyond the scope of this chaper.

Known Field Technique

Thermal neutron sources

There are no naturally-occurring sources of thermal neutrons but they can be obtained by placing a moderator around a fast neutron source. However, for practical purposes the fluence rate is usually very small in this case. When making a thermal source in this matter it is very important to make measurements with and without a Cd cover to determine how well the source has been thermalized.

TABLE 2.13 DE PANGHER LONG COUNTER EFFICIENCY RELATIVE TO THAT OBTAINED USING A ^{252}Cf SOURCE [1]

ENERGY MeV	RELATIVE EFFICIENCY	ENERGY MeV	RELATIVE EFFICIENCY	ENERGY MeV	RELATIVE EFFICIENCY
0.02	0.933	2.10	1.031	4.96	0.958
0.10	0.933	2.20	1.033	5.00	0.959
0.20	0.933	2.40	1.029	5.25	0.958
0.30	0.933	2.60	1.021	5.30	0.957
0.40	0.934	2.80	1.000	5.36	0.913
0.50	0.939	2.90	0.975	5.40	0.942
0.60	0.948	2.95	0.962	5.45	0.946
0.70	0.961	3.00	1.019	5.60	0.947
0.80	0.979	3.10	1.010	5.80	0.943
0.90	1.001	3.20	0.988	6.00	0.935
1.00	1.024	3.40	0.961	6.10	0.929
1.10	1.041	3.60	0.955	6.20	0.919
1.20	1.047	3.80	0.955	6.22	0.864
1.30	1.050	4.00	0.959	6.26	0.864
1.40	1.050	4.20	0.955	6.30	0.888
1.50	1.049	4.25	0.950	6.35	0.917
1.60	1.046	4.30	0.941	6.40	0.922
1.70	1.043	4.35	0.945	6.50	0.925
1.80	1.040	4.40	0.949	6.60	0.940
1.90	1.039	4.60	0.959	6.70	0.931
2.00	1.037	4.80	0.961	6.80	0.930
2.05	1.035	4.90	0.959	6.90	0.929
2.08	0.959	4.93	0.942	7.00	0.928

[1] From BSC 0813.

Moderated neutron sources

One way to achieve a neutron spectrum with a lower average energy than that of a fast neutron source is to place moderators of various material around a fast neutron source. Livermore Laboratory reported (Griffith et al., 1978) results with spheres of polyethylene, D_2O and Al surrounding the pneumatic source-transfer head for neutrons from Cf and PuBe sources. The fluence and dose rate for a 15 cm radius D_2O sphere surrounded by 0.02 inches of Cd (see Schwartz, 1980 for construction details) with a Cf-252 source at the center has been reported by Ing and Cross (1983). The reference field fluence rate for Cf with source strength $\dot{S}_o$ neutrons per second is

$$\dot{\Phi}_R = 0.89 \frac{(\dot{S}_o/4\pi)}{r^2} N \qquad (2.55)$$

where $N = N_A N_{AS} N_{SA} N_{RR} N_{BKG} N_T N_{NI} N_D$ and the factor 0.89 accounts for neutrons moderated to energies below the Cd cutoff. The attenuation coefficient in N should be averaged over the moderated spectrum.

The conversion factor for this spectrum is 9.0×10^{-6} mrem cm², so the dose equivalent rate is

$$\dot{H}_R = 2.29 \times 10^{-3} \frac{\dot{S}_o}{r^2} N \qquad (2.56)$$

where $\dot{H}_R$ is in mrem/hr, and $\dot{S}_o$ is in neutrons/sec.

Fast neutron sources

For a given source strength, the fluence in the reference field is

$$\dot{\Phi}_R = \frac{(\dot{S}_o/4\pi)}{r^2} N \qquad (2.57)$$

where N is the same as for Equation 2.55. Hence the attenuation coefficient should be averaged over the Cf-252 spectrum. For Cf-252, the conversion factor from fluence to dose equivalent (Schwartz, 1982) is 3.33×10^{-5} mrem cm², so

$$\dot{H}_R = 9.54 \times 10^{-3} \frac{\dot{S}_o}{r^2} N \qquad (2.58)$$

with $\dot{H}_R$ in mrem/hr and $\dot{S}_o$ in neutrons/sec.

Effective Center Correction

There is one other important correction for calibrating neutron instruments with sources which has not yet been discussed. This is a correction for the effective center of the instrument being calibrated. For spherical neutron detectors and point sources, the fluence at the geometric center of the detector should be increased by a factor of approximately $(1 + (r/d)^2/6)$ where r is the radius of the sphere and d is the distance from the source to the geometric center of the detector (see Axton, 1972; Harrison, 1981). The correction factor for other geometry detectors or sources will be different.

Beta Instrument Calibration

At present, the usual reference instrument for beta particle measurements is an extrapolation chamber. Due to the complex nature of this instrument, it is mainly used in a laboratory setting. Use of an extrapolation chamber to measure the output from beta sources allows them to be standardized in terms of absored dose to air or to tissue by applying appropriate stopping power ratios. To obtain uniform beams it may be necessary to use beam flatteners which in turn will affect the beta spectrum. Air absorption and scatter also affect the beta spectrum.

Reference Instrument Technique

The extrapolation chamber is an ionization chamber which behaves as a Bragg-Gray cavity in which the separation between the anode and cathode can be varied so measurements of ion current at various distances can be made and the results extrapolated to zero plate separation.

The absorbed dose rate to air, $\dot{D}_A$, is

$$\dot{D}_A = \frac{W}{e} \frac{k'}{A\rho} \frac{d}{dx} (i_u k(x)) \qquad (2.59)$$

where W/e is the average energy to produce an ion pair in air per electric charge (33.85 J/^{o}C = 33.85 eV/ion pair; ICRU 31, 1979), A is the effective area of the collecting electrode, ρ is the density of air, x is the chamber separation (see Loevinger and Trott, 1966, for effects of chamber separation correction due to dependence on plate voltage), i_u is the ionization current due to ion rate for a chamber built with walls fully matched to the chamber gas with respect to atomic number, and k', and k are correction factors (see Eur 7365, Böhm 1980, 1976).

Known Field Technique

A draft international standard recommends using C-14, Pm-147, Tl-204, Sr-90 + Y-90 and Ru-100 + Rh-106 sources as standards. It gives criteria for residual maximum energy based on range, on beam uniformity, and approximate dose rates at specified distance per unit activity with certain beam filters being present.

Table 2.14 lists recommended point sources (Owens, 1972), flattening filters, and the approximate dose rate at the calibration point per unit activity of the source.

Another common source to calibrate beta instruments is a uranium slab. The surface dose due to beta particles from a uranium slab is approximately 230 mrad/hr.

Additional information on calibration instruments for measuring short-range radiation can be found in IAEA 150 (1973).

TABLE 2.14 BETA SOURCE CALIBRATION INFORMATION [1]

RADIONUCLIDE	CALIBRATION DISTANCE (cm)	SOURCE TO FILTER DISTANCE (cm)	FILTER MATERIAL AND DIMENSIONS	APPROXIMATE DOSE TO TISSUE PER UNIT ACTIVITY mrad·h^{-1}·mCi^{-1}
^{147}Pm	20	10	1 Disc of polyethylene terephthalate of radius 5 cm and mass per area 14 mg cm^{-2} with hole of radius 0.975 cm at center.	23
^{204}Tl	30	10	2 Concentric discs, 1 disc of polyethylene terephthalate of 4 cm radius and mass per area 7 mg cm^{-2} plus 1 disc of polyethylene terephthalate of 2.75 cm radius and mass per area 25 mg cm^{-2}.	250
$^{90}Sr + ^{90}Y$	30	10	3 Concentric discs of polyethylene terephthalate each with mass per area of 25 mg cm^{-2} and of radii cm, 3 cm and 5 cm.	240

[1] Based on Owens, 1972.

Alpha Instrument Calibration

Instruments for measuring alpha particles usually fall into one of two classes mentioned in Section 2.4.5, namely, field instruments used to monitor for the presence of alpha radiation, or laboratory instruments for measuring the alpha activity in specially prepared samples. The latter is covered very well in NCRP Report 58 and is beyond the scope of this chapter.

Instruments used in the field are normally calibrated using the known field technique.

Due to the short range of alpha particles in materials, there is significant absorption in the instrument walls, in air, and in the source itself. This means that even instruments calibrated in a specific geometry with a calibrated source may require large corrections when used in the field.

Sources used to calibrate alpha instruments should be standardized in terms of activity, activity per unit area, emission rate, or emission rate per unit area. Ideally, the source area should be larger than the detector area (see Ballard, 1981) so that the entire active volume of the detector is irradiated. If smaller sources are used it will be necessary to form some kind of averaging procedure to irradiate the entire active volume.

2.5 CALIBRATION LABORATORY

The building space, facilities, equipment, staff and methodology necessary to properly operate a calibration laboratory depend on the volume and type of work undertaken. Calibration facilities exist that employ from a fraction of an employee's time up to tens of people. A brief description (taken largely from IAEA 133, 1971) of a typical medium-sized calibration laboratory is given as a guide to people that might have the responsibility of setting one up.

2.5.1 Building Space

The building for the calibration laboratory and the land on which it is located need to be closely integrated. There is a need to have a low scatter building so that calibration work may be completed with the required accuracy and that there be a low radiation level at external building walls. These conditions can be met by a relatively large building so that the inverse square law and moderate sheilding in the outer walls will reduce the dose-rate from exposed radiation sources and radiation generating machines to acceptable levels at the exterior of the building walls. The construction of a moderate-size building on a large lot, which can have rigidly controlled access so that the external environment at the building wall need not be reduced to non-control levels, is preferred on a cost basis. In areas of high land cost, however, this alternative may not be preferred and a moderately large building with adequate external wall sheilding may be required. In any case, the variation in the scatter at the positions of instrument calibrations should not exceed the variations due to instrument positioning on the test irradiation assemblies.

For certain types of work shielding is very necessary for reasons other than protection. Instruments that measure levels of radiation at or slightly above background are best calibrated in an area with low background. When other external radiation sources are nearby, additional shielding will serve to keep the background levels within the calibration cell constant.

Special features of the building should include shielded film and other personnel dosimeter detector storage areas of constant low background radiation and controlled temperature and humidity so that dosimeters can be stored before and after exposure. In the design of the laboratory building, flexibility in the use of all of its facilities should be provided. Maximum requirements include 1) irradiation rooms; 2) radiation source storage vault; 3) personnel dosimeter detector storage vault; 4) administration offices; and 5) receiving and shipping areas.

2.5.2 Facilities

To carry out the calibration program, a laboratory requires properly designed and instrumented assemblies (sometimes called jigs or rigs) to position the test dosimeters, or portable instruments in proper relationship to the source. The number, size, and complexity of the laboratory assemblies will depend on the type of radiations, instruments, and dosimeters needed, and on the amount of calibration carried out. For laboratories that calibrate large numbers of the same type of beta-gamma survey instruments, calibration wells have the advantages of low exposure to the operators, of utilizing less floor space and of very little handling of the source.

Working conditions in the calibration laboratory should not cause excessive radiation exposure to personnel. Personnel exposure should be kept as low as practical and should in no case under normal operating conditions exceed levels allowed by regulation. To meet this condition, personnel shielding, remote instrument reading and positioning facilities, automatic source handling mechanisms, and other mechanical or remote operations are recommended.

2.5.3 Staff Qualifications and Training

The size and nature of the laboratory staff depend on the position of the laboratory in the organizational hierarchy (i.e., on the calibration accuracy required) and on the volume of the business. In a typical medium-sized laboratory the staff might consist of a director, a physicist, several technicians and a secretary. This provides a staff of two professional qualified persons to look after the scientific aspects of the laboratory work and several technicians to assist in the performance of the routine aspects of the laboratory calibration program. The technical integrity of the laboratory should be above reproach, and a competent staff of recognized capability is required to ensure this status.

The qualifications of each member of the laboratory should be carefully reviewed to ensure an experienced and capable staff. This type of laboratory should not be staffed with inexperienced personnel.

Ideally, the manager should have an academic degree in one of the sciences, mathematics or engineering, and should have a minimum of five years practical experience in personnel dosimetry and radiation monitoring programs. The manager should understand the basic pronciples involved and be competent in the use of the reference and other standards of the laboratory and its equipment. For example, competent use of reference ionization chambers, extrapolation chambers, R-meters, precision long counters and similar radiation measuring equipment should be understood so that proper calibration can be provided. The manager should possess a good understanding of statistics and the application of statistics and mathematical analysis to the quality control programs. Finally,

the manager should have demonstrated good administrative capabilities, ability to issue clear and concise scientific reports, and work well with people.

The physicist should have earned a degee or an equivalent qualification in one of the physical sciences, mathematics, or engineering, and a miminum of two years experience with personnel dosimetry and radiation monitoring. In general, the physicist should have knowledge, experience and capability in all areas prescribed for the manager.

The technicians are required to assist in making the exposures. The capabilites and experience of the technician should lie in the field of physical sciences. Experience in calibrations and radiation protection or health physics activities is desirable.

A secretary who should have the qualifications established for advanced secretarial positions is required for the organization. Duties wil include the preparation, filing and maintenance of the record copies of the calibrations as well as the conventional secretarial duties as directed by the laboratory manager and the physicist.

2.6 PRACTICAL DETAILS IN CALIBRATING INSTRUMENTS

All calibration procedures begin with the arrival of the equipment to be calibrated, continue with preliminary system checkout, calibration, and then end with certification and shipping of the equipment. This total procedure must be documented in a checklist form since every step is an important part of the calibration process. In the following sections, items that should be covered by such a checklist are reviewed.

2.6.1 Initial Set-up

Any radiation measuring equipment may be contaminated when it arrives at a calibration facility. Therefore, each item must be checked before being admitted to the calibration procedure. Generally this is done using a pancake proportional counter (Chapter 4) or GM counter (Chapter 5). To determine the presence of removable contamination, a wipe sample could be taken and counts from the sample detected by a gas flow proportional counter, solid state detector, thin window GM tube, etc. For an accurate determination of the amount of removable contamination present it will be necessary to identify the radionuclides on the wipe sample and correct the observed count rate for experimental conditions.

A more serious problem from the standpoint of health safety may be a gross contamination of an instrument by tritium, which normally is measured by a wipe sample counted in a liquid scintillation system. If an instrument came from a facility where large volumes of

tritium are used or processed, such as a medical research facility, special procedures should be used to insure that the equipment arrived "clean." A similar situation arises when a stationary system is to be calibrated. A check of background should be done in order to be certain that no gross contamination is present that may 1) alter the accuracy of the calibration; or 2) contaminate the portable tools used in calibration (radionuclide sources, ionization chambers, screwdrivers, etc.). Also, a check for extraneous sources that may inadvertently be placed in a location that will affect the calibration is necessary.

All unshielded electronics are affected by radiofrequency interference, therefore it is prudent to check for the presence of large sources of radiofrequency radiation. For example, one should neither use nor calibrate a low level proportional counter in a room that adjoins an arc welding facility. Radio transmitters (including radar) are well known to cause interference to ionization chamber instruments.

Other obvious items should be checked in incoming equipment shipments, for instance:

1. Does the equipment belong at this calibration facility?
2. Are all parts present and are they matched?
3. Is the equipment clean (exterior appearance)?
4. Is anything broken (broken meter glass may signify rough handling and the chance of an intermittent failure that could affect calibration)?

Before initiation of the calibration procedure, appropriate paperwork should be assigned to each piece of equipment since the calibration is virtually useless if it is not documented.

It should be obvious that non-facility related equipment should be restricted. For example, an incident occurred in a nuclear research facility in 1965 where a researcher was disassembling an old sextant in a room adjoining the counting lab. His intention was to clean up this antique and display it in his home. He found some crusty white material near the reticule and removed it letting some of it scatter on the floor. After all, it was just corrosion! The next morning the counting lab was unusable because of external high background levels. "Corrosion" in the sextant was a radium compound used to illuminate the reticule at night. This radionuclide and its daughters were transported throughout the building not only by the shoes of the laboratory's personnel but also by the arrival and subsequent decay of the radium daughter "randon," a gas. Much time, money, and effort had to be committed in cleaning up the building. The counting lab from that time on had a new elevated quasi-permanent background level.

2.6.2 Equipment Checkout

The proper procedure would include a complete check of both the electronics and mechnical functions of an instrument before beginning the actual calibration procedure. The batteries should be checked with an external battery checker and not merely with the "Battery Test" switch on the instrument being calibrated. This is also applicable to stationary instruments. For most instruments, detailed steps for accomplishing these tasks are incorporated into the operations manual by the manufacturer. They should be itemized on a checklist as part of the normal calibration procedure.

2.6.3 The Actual Calibration

Calibration involves a combination of electronics and ionizing radiation procedures. For example, the sensitivity of an ionization chamber to ionizing radiation is a funciton of 1) the voltage placed on the electrodes of the chamber (Chapter 3) in that it must be on the plateau region (which is a function of chamber gas content and electrode design and spacing) and 2) the proper adjustment of the various circuits that will measure signal current. But it is also a function of several characteristics that have no direct relationship to electronics but only to the incoming radiation, such as 1) the area of the chamber electrodes, 2) the construction of the chamber wall, and 3) the energy of the incoming radiation. Thus, both electronic adjustments and radiation exposure are required to facilitate the calibration of an ionization chamber. This principle applies to all radiation measuring equipment from a small TLD (thermoluminescent dosimeter) chip to the totally computerized GeLi semiconductor detector spectroscopy system.

Each instrument calibration at the laboratory should have a protocol stating explicitly what steps should be followed in its calibration. This protocol should include at least the following 1) how the standard is used (i.e., what techniques in Section 2.4.5 are used), 2) what in-house quality control procedures should be used prior to calibration, 3) what radiation sources are used and at what field strength the instrument should be calibrated, 4) what precalibration checks are needed, 5) what setup procedure should be used during the calibration, and 6) what corrections must be applied.

The raw data should be taken and recorded in such a manner that it can readily retrieved and examined if in the future there is some question about the calibration of a particular instrument.

Since each step in the calibration procedure will contribute some uncertainty to the overall calibration, care should be taken at each step to ensure that the resulting total uncertainty does not exceed that claimed by the laboratory for calibrating that particular type of instrument.

2.6.4 Possible Sources of Inaccuracy in Calibrating Instruments

Table 2.15 gives typical sources of inaccuracy encounterd in instrument calibration. Most of these sources of inaccuracy were discussed in Section 2.4.5. In the ideal case all of the typical sources of inaccuracy listed, plus any others which are specific to the particular calibration set-up involved, will have been evaluated to arrive at an overall estimate of the accuracy of the calibration.

The possible sources of inaccuracy listed in Table 2.15 are primarily associated with "hardware." The table is subdivided into various areas associated with the calbration process (i.e., the survey instrument to be calibrated, the set-up apparatus, and the reference standard - either a radioactive source or an instrument). In addition to these errors, there are also errors associated with the "metrologist" such as:

- general laboratory procedures (carelessness, leaving unattended check sources about, etc.)
- mishandling or mistreating the apparatus
- failure to check that equipment is operating properly
- applying a calibration method not suitable for the instrument being calibrated
- misreading instruments and ancillary apparatus
- computational errors
- using incorrect values for correction factors

2.6.5 Calibration Report

The final product of the calibration is a calibrated instrument and its calibration report. This report should clearly state the calibration conditions. After the report is completed, it should be examined for obvious "blunders," i.e., misplaced decimal points, unreasonable correction factor for that instrument, etc. Ideally, the report should be examined by at least two staff memebers at the calibration laboratory before it is issued.

2.7 QUALITY CONTROL

Quality control ultimately is as good or as bad as the person in charge of the calibration facility wants it to be. The product of the facility is calibration and maintenance of radiation measuring equipment and nothing else. For this reason the equipment that leaves the facility should be in perfect operating condition, adequately documented and, of course, calibrated to a known accuracy.

TABLE 2.15 POSSIBLE SOURCES OF INACCURACY IN INSTRUMENT CALIBRATION

1. TYPICAL SOURCES OF INACCURACY ASSOCIATED PRIMARILY WITH THE SURVEY INSTRUMENT.

Voltage supply instability
Insufficient electric field strength to collect all the ion pairs
Pulsed radiation field measurement
Stabilization time
Switching transients
Capacitance effects
Overload characteristics
Dead—time effects
Drift in instrument electronics
Radiation—induced leakage
Response in extracameral volumes
Geotropism
Directional or orientational dependence
Response to stray RF or magnetic fields
Response to radiation scattered by the calibration set—up
Response to radiation scattered by the room
Response to other radiation (e.g., response to gammas emitted by a neutron source)
Attenuation in components of survey instrument
Vented ion chambers becoming sealed
Temperature and pressure corrections for vented ion chambers
Humidity
Energy response of instrument
Insufficient wall thickness for charged—particle equilibrium
Inherent imprecision of instrument
Statistical variation in amount of charge collect due to
- fluctuations in number of incident photons, neutrons, etc.
- variation in the energy of the primary charged particle produced by the incident radiation
- Poisson distribution in the number of ion pairs produced
- Instantaneous fluctuations of exponential discharge—charge characteristics of input circuit

2. TYPICAL SOURCES OF INACCURACY ASSOCIATED PRIMARILY WITH THE CALIBRATION SET—UP.

Reproducibility of placement of survey instrument in set—up
Length of time of exposure
Uniformity of beam across survey instrument detector
Uniformity of beam throughout active volume of detector
Using a collimated beam smaller than the detector
Air attenuation of the calibration beam
Uniformity of additional filtration
Kilovoltage of x—ray unit (both its value and stability)
Half—value layer measurement
Failure of field to follow inverse square law
Scatter from set—up apparatus
Energy spectrum change due to scattering within a calibration well

3. TYPICAL SOURCES OF INACCURACY ASSOCIATED WITH USING A CALIBRATED RADIOACTIVE SOURCE TO CALIBRATE THE SURVEY INSTRUMENT.

Uncertainty of reference source calibration
Radionuclidic impurity
Decay corrections
Attenuation in air
Attenuation within source and its holders
Anisotropic emission from the source
Scatter from source components (i.e., shutters, collimators, etc.)
Source not monoenergetic (this may be intentional for some calibrations)
Multiple types of radiation present (i.e., gammas and betas from Co—60)
Uncertainties in decay scheme (needed to evaluate the exposure rate constant)
Radiation leakage from source container

TABLE 2.15 (Continued)

4. TYPICAL SOURCES OF INACCURACY ASSOCIATED WITH USING A REFERENCE INSTRUMENT TO CALIBRATE THE SURVEY INSTRUMENT.

Uncertainty in *reference instrument* calibration
Energy response of the reference instrument (particulary if calibration at one energy and used at a different energy)
Electrometer leakage current
Leakage of charged capacitor in capacitive—feedback electrometers
Ionization chamber electrical leakage
Power supply fluctuations
Electrometer (stability and accuracy)
Many of the possible sources of inaccuracy listed under survey instrument (Item 1) apply equally well here

A good quality control system will include:

1. Documentation of the maintenance and calibration steps that an instrument must undergo from entry to exit and a check sheet that indicates that these steps were taken.
2. A detailed description of each step so that instrument adjustment or calibration will be performed properly.
3. Availability of all tools required to accomplish the defined tasks.
4. An inspection system that assures the proper calibration and maintenance of each instrument.
5. A maintenance and calibration certification affixed to the instrument.
6. A system of inventory control that not only keeps track of the instruments in the calibration laboratory, but also all those assigned to be calibrated at the facility. This should include an automatic recall system so that calibration cycles are properly adhered to (usually every 6 months to 1 year depending on the instrument and conditions of its use).
7. Control over repair parts so that they meet the specifications set forth by the manufacturer.
8. An in-house program to monitor the constancy of the equipment used for establishing the reference radiation field.

If the above controls along with others that may fit a particular facility are adhered to, a fully operational and calibrated instrument will be delivered.

2.7.1 Frequency of Calibration

Apart from any legal requirements, it is recommended that an instrument should be calibrated at least once every 12 months, or more frequently under severe conditions of use. A newly purchased instrument should also be calibrated before putting it into service. In addition to determining the correction factor, this initial test should check the scale linearity and range-change errors. If the

instrument has suffered any damage or has been repaired, then adequate checks should be made to ensure that the original calibration is still valid; if not, then a recalibration should be undertaken.

The reference instrument (standard) used by the calibration facility should also be periodically compared to an instrument in the next higher level of the standards hierarchy. In some countries intervals of perodical checking are determined by special regulations. Where no such regulation exits the frequency of the calibration depends on the nature of the reference instrument as well as upon the procedure adopted to check its constancy. Where the reference instrument is in the form of a detector, e.g., an ionization chamber, it should be checked again approximately once every twelve to twenty four months. For standard sources a very much longer period is acceptable.

2.7.2 Constancy Checks

Between the regularly scheduled calibrations the user should carry out constancy checks. Where possible these should be made with the same type of radiation for which the instrument is used. A jig incorporating a gamma source may prove to be useful in checking a gamma-beta instrument. Some instruments have built-in check sources that can be used to provide constancy checks.

Constancy checks are doubly important when the instrument is used in high level radiation areas or when the instrument is used only occasionally. The leakage radiation from a reactor or accelerator operating under a fixed known condition can also be used to see if the instrument sensitivity has changed since it was last calibrated. If a change occurs the instrument should not be re-adjusted to give the original constancy check reading since external factors could have changed its characteristics. This is better done at the calibration laboratory where a wider range of standard sources may be used to check the sensitivity over the instrument's complete range.

2.7.3 Mechanical, Electrical and Environmental Evaluation

Performing a full "type-test" evaluation of an instrument will assist in the proper selection, operation and calibration of radiation monitoring instruments. The limitations of an instrument should be made known to the users, since they may often be as important, or more so, than its good features.

Calibration in the radiation environment alone does not constitute the complete "type-test." Other significant influences which should be included are (see also IAEA 133):

1. Mechanical effects:
   a) Shock and moisture resistance.

b) Resonance effects (vibration).
c) Geotropism.

2. Normal environmental effects:
   a) Temperature dependence.
   b) Humidity dependence.
   c) Atmospheric pressure.
   d) Capacitance effects.
   e) Chemical degradation.

3. Electromagnetic interference effects:
   a) Magnetic fields.
   b) RF fields.
   c) Electrostatic fields.
   d) AC line transients and noise.

4. Extra-cameral effects.

5. Electronics design:
   a) Power supply stability.
   b) Battery life.
   c) Linearity.
   d) Sensitivity.
   e) Switching transients.

6. Human engineering.

The references in Section 2.1 give additional information on "type-testing" instruments.

The ideal instrument would be designed to operate in the presence of all of the above effects and still provide accurate readings. This, of course, is never possible but with some additional expense most of the normal problems can be alleviated. This is the reason why, for example, the majority of military survey meters are very different in both physical and electronics design from commercial instruments of equivalent apparent capability. Notably, military instruments are very resistive to mechanical and environmental influences.

2.8 TRACEABILITY AND QUALITY ASSURANCE

The concept of traceability is both important and elusive. Indeed, after many years of debate by recognized authorities there still does not exist a single definition of traceability that is acceptable by the entire scientific community (Belanger, 1980). A favored definition (op.cit.) is the following:

"Traceability to designated standards (national, international, or well characterized reference standards based upon

fundamental constants or nature) is an attribute of some measurements. Measurements have traceability to the designated standards if and only if scientifically rigorous evidence is produced on a continuing basis to show that the measurement process is producing measurement results (data) for which the total measurement uncertainty relative to national or other designated standards is quantified."

If should be noted that traceability is sometimes also defined in a way that emphasizes NBS calibration of an artifact (instrument, source), or calibration against another standard in a chain or echelon of calibrations, ultimately leading to a calibration performed by NBS. A comparison of these two definitions provides perhaps the clearest exposition of two contrasting views of traceability, the one stressing characteristics of measuring instruments or standards, the other stressing requirements relating to quantifying measurement uncertainty. The one regards accuracy as a property of an instrument, whereas the other focuses on the quality of measurements.

A basic requirement of any measurement or calibration is consistency with the national standards. Measurement consistency can be demonstrated or implied. The user or regulating authority must ultimately decide whether implied consistency is adequate, or whether it must be demonstrated. In either case, some action or actions must be taken if consistency is to be achieved. If these actions are performed properly the measurement is considered to be consistent with the standard. It is essential that the steps taken be documented. Such documentation is the only evidence that the actions were taken and were appropriate.

2.8.1 Instrument Traceability

In those cases where implied consistency of a measurement with a standard is sufficient, it can be achieved through a calibration process (Eisenhower, 1982). The instrument used to make the measurement is calibrated by comparison with the appropriate national standard, either directly or indirectly through intermediate calibrations as shown in Figure 2.10. This is the traditional type of traceability. In some cases it is the only kind that can be realized because of inadequacies in the measurement support system. Radiation sources are frequently utilized in the instrument calibration process and should therefore also be calibrated in a manner that provides traceability to the appropriate national standard.

A shortcoming of instrument traceability lies in not being able to demonstrate that the measurement made with a traceable instrument is indeed consistent with the national standard. The consistency of the measurement must be implied inasmuch as the traceability chain ends with the instrument (Figure 2.10). Under favorable conditions a measurement made with a traceable instrument may be consistent with a

standard. Some degree of uncertainty about the validity of the result remains, however, since the quality of the measurement itself has not been demonstrated.

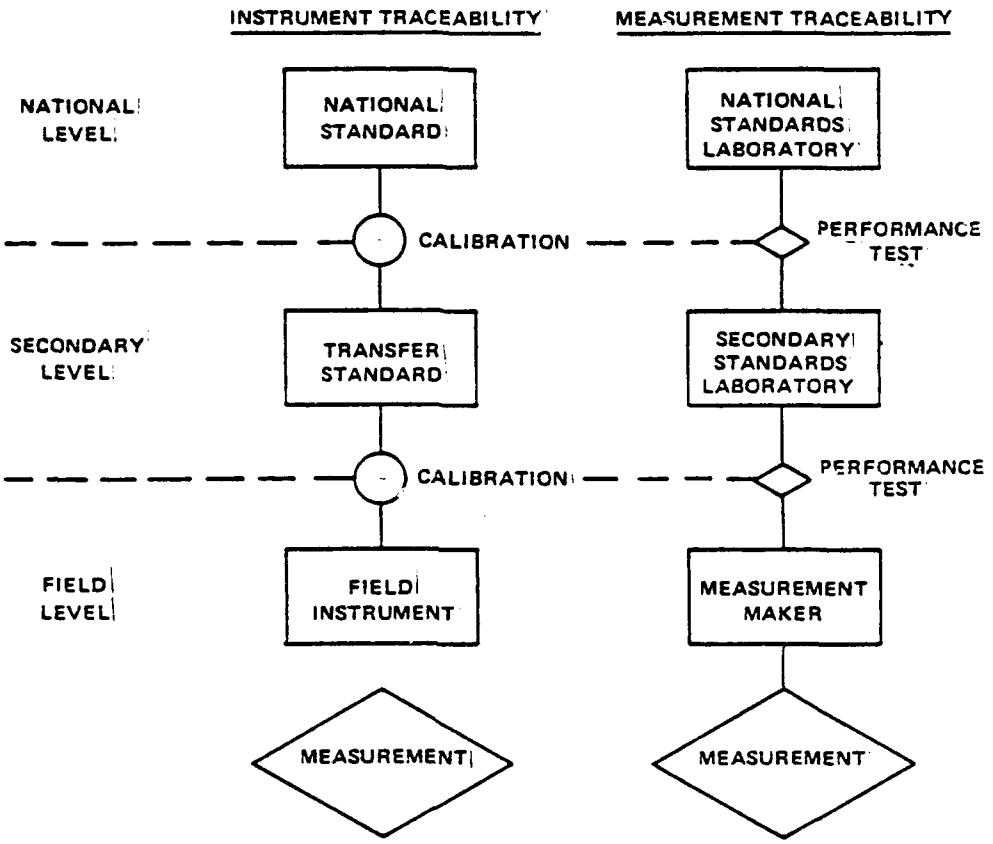

FIGURE 2.10 TRACEABILITY CHAINS FOR INSTRUMENT TRACEABILITY AND MEASUREMENT TRACEABILITY (EISENHOWER, 1982).

2.8.2 Measurement Traceability

For demonstrated consistency of a measurement with a standard the traceability chain must extend beyond the instrument to the measurement (Figure 2.10). In this case, traceability becomes a characteristic of the measurement itself, and there is documented evidence that the measurement is consistent with the appropriate standard. Measurement traceability is the most desirable type of traceability, since it is based on a demonstration that the complete measurement process is performing as intended, including the instrument, its user, and the procedures.

Measurement traceability is usually achieved by using a transport standard. This standard may be in the form of a radiation

source, instrument or a dosimetry device that originates from NBS for the particular measurement under consideration. When a radiation source or instrument is used, its output or response is measured by the participant who recieved it, and the result is reported to the originating laboratory. If the reported value compares favorably with the value determined by the originating laboratory, a statement of satisfactory performance is provided to the participant.

When a dosimetry device is used as a transport standard, it is sent to the participant who gives it a nominal dose (or exposure). The dosimeter is then returned to the originating laboratory, where the dose (or exposure) is evaluated. If the participant's nominal measured value is within the acceptable range of uncertainty, a statement of satisfactory performance is provided. An important advantage of measurement traceability is that it can be achieved without the need of a transfer standard (instrument or source) that has been calibrated by NBS.

2.8.3 Measurement Quality Assurance

It is important to stress at the outset that the resolution of the issue of whether or not a particular system for realizing traceability is effective depends entirely on the real intent of traceability, i.e., to insure measurement of adequate accuracy. As indicated above, it is evident that mere calibration of a standard instrument by NBS, although perhaps necessary, is not sufficient for the task at hand. What is required for traceability is to demonstrate that the measurement process indeed produced "measurement results (data) for which the total measurement uncertainty relative to national or other designated standards is quantified." This key step demands careful definition of the quality assurance requirements for the particular measurement under consideration, and implementation of a systematic procedure to affect the desired demonstration. For ionizing radiation, the systematic procedure is commonly referred to as a Measurement Quality Assurance (MQA) Program, i.e., a program that allows one to demonstrate that the total measurement uncertainty including both random and systematic components of error relative to national or other designated standards is quantified, and sufficiently small to meet the requirements of the measurement process.

The development of a good MQA program requires a clear definition of the objectives, i.e., what is to be measured and what accuracy is required. A second step is to develop a model of the physical measurement process, i.e., what are the factors that affect the precision and accuracy of the measurement results? Next, the development of a suitable transport standard is a critical part of the development of a MQA program. The transport standard is a device, artifact, or material that must be stable, rugged, and well-characterized, and whose value is accurately known relative to national standards. Between measurements made on the transport

standard at NBS it can be sent to the laboratories participating in the MQA program so that they can make measurements on the transport standard and thereby determine biases relative to NBS. Essential requirements for a transport standard are transportability and predictability.

For some measurements it is necessary for NBS to design and build a transport standard. In other cases it is possible to find a commercial instrument or device that is sufficiently stable to serve as the transport standard.

Finally, development of proper methodology is also very important. NBS generally makes recommendations to new users of MQA services as to good operating practices and provides consulting help to the participants as needed, so that each participant can have the best possible measurement quality assurance procedures within the capabilities of the laboratory. Users of MQA services should also conduct constancy checks that will monitor the stability of their reference standard and measurement or calibration procedures, and provide data on precision.

Measurement quality assurance services have been developed in the field of ionizing radiation that are suitable for use with photon dosimetry, electron dosimetry, and radioactivity measurements.

If all of the MQA program procedures recommended by NBS are followed, not only will the laboratory know when a problem arises, but they will also have data available that will make it possible to locate the source of the problem readily and correct it. Thus, participation in a MQA program provides feedback to permit self-correction action by the participant.

It is not uncommon for a laboratory participating in a MQA service for the first time to uncover a systematic error in their measurement process that has gone undetected for years. The other situation also surfaces, in which a laboratory has made conservative estimates of their measurement uncertainty and then finds after participating in a MQA program, that they can document an uncertainty for their measurement process that is much better than they proviously estimated. The important point is that a MQA program provides a way for a laboratory to rigorously quantify its measurement uncertainty relative to national standards, and by so doing capture the elusive traceability.

2.9 LEGAL AND ETHICAL IMPLICATIONS

Failure to follow the best available practice in a radiation instrument calibration laboratory compromises the radiation protection of the very personnel for whose protection the calibration laboratory exists. Less than best effort cannot be condoned on ethical grounds, and will most likely lead to unnecessary, time consuming and expensive law-suits. There is indeed no substitute for following well thought out procedures that are updated as new

information, in the form of improved measuring instruments and sources, better calibration techniques and/or intervals, revised maximum permissible dose levels, etc., is received. It is important to realize that following technically good calibration procedures is not sufficient. These procedures must be accomplished by quality assurance programs that demonstrate that the desired accuracy is indeed being realized. Informed, conscientious operation of a calibration laboratory will satisfy existing legal requirements (Chapter 12), and will reflect a high degree of professional ethics.

2.10 SUMMARY

The basic principles necessary to an informed approach to the calibration of the most common ionizing radiation measuring instruments were presented. This was accomplished by first describing the organizational structure of the ionizing radiation measurement community and the hierarchy of radiation standards. Emphasis was placed on the national standards which are based on fundamental physical constants. Less detail was devoted to the various types of transfer standards obtained by comparison with the national standards.

The two principal technique (known field and reference instrument) for calibrating instruments were discussed. General features of radiation sources used for calibrating instruments for x rays, gamma rays, beta particles, alpha rays and neutrons were reviewed. This was followed by a summary of the various types of instruments used for measuring radiation and which calibration techniques are commonly used to calibrate various types of radiation measuring instruments. There was a lengthy discussion of how the reference field at the calibration point and at the time of calibration is determined by both calibration techniques and for various radiation types.

General features of a typical medium scale calibration laboratory were described. This was followed by practical details of instrument calibration, including an estimate of the inaccuracies in the calibration process.

Quality control was then discussed in the context of calibration intervals, constancy checks and mechanical, electrical and environmental evaluation. A brief treatment of safety precautions was given. The important concepts of artifact and measurement traceability were outlined and the need for a national measurement support system to facilitate traceability demonstration was indicated. Finally, the legal and ethical implications of good (or bad) calibration practice were presented.

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APPENDIX D. METHODOLOGY INVESTIGATION PROPOSAL

December 1988

1. TITLE. Nuclear Radiation Metrology Methods.

2. INSTALLATION OR FIELD OPERATING ACTIVITY. US Army Electronic Proving Ground, Fort Huachuca, Arizona 85613-7110.

3. PRINCIPAL INVESTIGATOR. Dr. D. Richard Sears, Command and Control Division, STEEP-CT-O, AV 821-8118, steepcto@epg1-hua.arpa.

4. BACKGROUND. Over the past four decades, there has been a continuing growth of nuclear radiation generators and sources. These include weapons, reactors, and new radionuclides. Nuclear capability and expertise in reactor and weapon technology have now spread throughout the world. Timely hazard assessment due to the use or misuse of nuclear devices can only be made by means of modern radiological instrumentation termed RADIAC (Radioactivity Detection, Identification, and Computation) by the Army. The nuclear radiations of particular interest to the military are the electromagnetic gamma radiation and the particulate alpha, beta, and neutron emissions. Detection and measurement of nuclear radiation is dependent upon the energy, time characteristics, and quantity of radiation received at the RADIAC device. For nuclear weapon detonation, the radiation absorbed dose (rad), prompt neutron and gamma radiation up to 10,000 rads per microsecond must be measured. For radioactive fallout, contaminated items or commodities using radioactive devices, continuous alpha, beta, and gamma radiation levels as low as 0.001 rad must be measured. This project is a new investigation.

5. PROBLEM. This investigation is to develop test methods and identify instrumentation required to support tests of nuclear radiation measurement devices, calibration devices, and associated equipment such as charger-readers. Most military radiation instruments are designed to measure the tissue absorbed dose or dose rate received by personnel. Methods, techniques, and appropriate instrumentation to measure the energy dependence, rate dependence, neutron radiation, and mixed radiation for instruments under development are poorly defined and in some cases nonexistent. The importance of effective test and evaluation of nuclear instrumentation parallels that of a gas mask or parachute. If and when these devices, such as a field tactical dosimeter, need to be employed, the user must have confidence in its proper operation. By contrast, other Army materiel such as transportation or communications equipment are generally operated in a near total design environment and can subsequently be "debugged" on the basis of field reports. This cannot be done for tactical nuclear instrumentation due to treaty restrictions preventing atmospheric nuclear weapons testing. Improved test methods and simulators are needed, and could contribute to an improved survival rate during a nuclear conflict.

6. OBJECTIVE. This investigation will develop test procedures and recommend instrumentation for the test of RADIAC instruments. Special emphasis will be placed upon the accuracy of tissue dose or dose rate measurement accuracy considering radiation energy and rate dependence for gamma and neutron radiation. A second priority will be to develop test procedures and recommend instrumentation to assess the measurement accuracy of alpha instruments considering

radiation energy while discriminating against beta radiation. Energy dependence subtests will consider the following ranges: gamma 10 KeV to 12 MeV, neutron 0.025 eV to 20 MeV, alpha 2 to 7 MeV, beta 15 KeV to 3 MeV. Rate dependence tests for tactical dosimeters will consider gamma, neutron, and mixed gamma neutron rates up to 10^{10} rads per second.

7. MISSION AREA SUPPORTED. COS.

8. PROCEDURES.

a. This investigation will consist of two phases --

(1) A survey of nuclear metrology procedures documented in technical publications, and a survey of techniques used by Government and industry.

(2) Laboratory experimentation to evaluate these methods for test of Army RADIAC instruments.

b. The investigation is to be primarily an in-house effort that will make maximum use of instrumentation existing in the USAEPG Radiological Test Facility. This facility was designed especially to test RADIAC instruments as opposed to nuclear effects testing. Energy dependence tests will employ a dual tube x-ray capable of producing simulated gamma radiation from 5 to 400 KeV. Because x radiation is spectral, filters must be interposed between the source and the test item to change the quality of radiation for energy dependence testing. A multichannel analyzer and energy selective detector probes are available to evaluate the radiation quality. Filter combinations recommended by NBS, CECOM, and other sources will be evaluated. For higher energy levels, radioactive sources at USAEPG or other installations will be investigated.

c. The rate dependence test will employ the USAEPG thermoluminescent dosimeter (TLD) system. This system can employ a wide variety of solid state detectors that are essentially rate independent. New detectors are available that are selective in response to gamma, neutron or alpha radiation. This effort will include obtaining new detectors, evaluating their potential use for Army requirements, and documenting test procedures. The use of high-power pulsed sources at other installations will be required.

d. Neutron dosimeters will employ the USAEPG 10-curie Plutonium-Beryllium neutron source together with the TLD system for initial test procedure development. This neutron source can also be used in conjunction with gamma sources to investigate mixed radiation dosimeter techniques. The use of reactor or accelerator sources of other installations will be required to complete the investigation.

e. This investigation will be accomplished over a 2-year period. Phase I is expected to be accomplished during the first year with a report which analyzes the results of the metrology and techniques investigation with recommendations on their use for Army testing purposes. Conclusions will be drawn as to whether these adequately satisfy Army needs or whether Phase II should be pursued. In the event Phase II is required, the results of the laboratory

investigations will be published at the end of that Phase. These results will establish procedures for tests of RADIAC instruments. It is expected that new TOPs will derive from this effort. USAEPG nucleonics personnel will pursue the task full time when not engaged in TECOM-assigned test projects. The investigation will be documented in a final report to include all procedures developed and recommendations for additional instrumentation to permit complete RADIAC testing at USAEPG.

f. Environmental Impact. This investigation will have no adverse effect on the environment.

g. Health Hazard. This investigation will subject personnel to the potential health hazards normally associated with a radiation laboratory. Control of these potential hazards will be by the same SOPs and safeguards which are currently used for all work in the radiation laboratory.

9. JUSTIFICATION/IMPACT.

a. Association with Mission. USAEPG's basic mission is to test and evaluate communications-electronics equipment including a broad range of surveillance systems. A significant part of this responsibility is to plan, conduct, evaluate, and report on the following types of RADIAC equipment:

(1) Alpha, beta, gamma, and neutron detecting and/or survey rate meters.

(2) Aerial survey gamma rate meters.

(3) Individual and personnel dosimeters.

(4) RADIAC training devices.

(5) Remote area monitoring systems.

b. Present Capability, Limitations, Improvements, and Impact on Test if not Approved. The basic capability to test RADIAC systems under safe conditions exists at USAEPG. However, the 1989-92 timeframe tests will be of devices that are much improved over the present technology. The proposed technology that includes solid state sensors and color changing dyes will present new problems that must be addressed during test and evaluation. Nuclear weapon development by the United States and other countries has advanced steadily over the past four decades. Fielding of modern RADIAC instrumentation has made little progress over the past 20 years. Instrumentation shortfalls include: the aerial RADIAC survey system, vehicular RADIAC system, and tactical dosimeter which can respond to and measure prompt neutron-gamma radiation from a nuclear burst. These items are now under various stages of development testing. Delay in developing adequate test procedures and instrumented test capability can result in fielding inadequately tested instruments. Procedures and test instrumentation must keep pace with advances in RADIAC development in such areas as radiation analyzers, pocket RADIAC, data integration system, and others.

10. DOLLAR SAVINGS. No direct savings are anticipated. The proposed investigation is to develop methods and an instrumented capability to effectively test new RADIAC devices that have new and stringent data requirements.

11. RESOURCES.

a. Financial.

(1) Funding-Breakdown.

	Dollars (Thousands) FY89		Dollars (Thousands) FY90	
	In-House	Out-of-House	In-House	Out-of-House
Personnel Compensation	40.0	--	41.0	--
Travel	8.0	--	9.0	--
Contractual Support	--	--	--	--
Consultants & Other Svcs	--	25.0	--	40.0
Materials and Supplies	12.0	--	6.0	--
Equipment	--	--	--	--
General & Admin Costs	--	--	--	--
Subtotals	60.0	25.0	56.0	40.0
FY Totals	85.0		96.0	

b. Explanation of Cost Categories.

(1) Personnel Compensation. Compensation chargeable to the investigation for using technical or other civilian personnel assigned to the investigation.

(2) Travel. Visits to Government, industry, and university facilities that have nuclear metrology capability.

(3) Consultants & Other Services. Charges assessed to use pulsed nuclear radiation facilities that exceed USAEPG's present capability to develop rate and energy dependence techniques. A consultant may be needed in FY90 for assistance in the theoretical analysis leading to the development and verification of measurement techniques.

(4) Materials and Supplies. Material and supplies include funds to procure x-ray filters, neutron filters, foils, moderators, TLD radiation detectors, and other devices that will be evaluated for their potential value to increase the effectiveness of the Army RADIAC test capability.

c. Obligation Plan. The actual obligation rate for this study will depend upon the TECOM assigned test workload that must be accomplished during the 2-year period. Due to the Nuclear Regulatory Commission (NRC) licensing provision, the nucleonics personnel at this installation must perform the experiments using licensed sources. There is not sufficient depth of personnel under license and having this type of training and expertise to commit their time solely to this investigation and still conduct assigned RADIAC tests. Between

assigned test projects, the nucleonics personnel will devote full time to this investigation. The obligation rate and the investigation schedule when required to be changed, will be coordinated with TECOM.

	FO	1	2	3	4
Obligation Rate FY90 (Thousands)		23.0	22.0	21.0	21.0

d. Manhours Required.

In-House: 1500
Contract: 500

12. ASSOCIATION WITH TOP PROGRAM. MTP/TOPs 8-2-172, RADIAC Survey Instrumentation and 8-2-064 will be reviewed. New procedures and techniques in nuclear technology appropriate for TOPs will be documented as new TOPs.

FOR THE COMMANDER:

ROBERT E. REINER
Chief, Modernization and Test
Technology Office

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APPENDIX E. GLOSSARY OF TERMS AND ABBREVIATIONS

GLOSSARY OF TERMS

absorbed dose	The quotient of the mean energy imparted by ionizing radiation to the matter in a volume element to the mass in that volume element.
alpha radiation	Radiation consisting of helium nuclei.
attenuator	Absorbing material placed in the radiation beam between the source and the target, in order to reduce beam intensity at the target.
bequeral (Bq)	The SI unit of radioactivity, 1 Bq = $1s^{-1}$.
beta radiation	Radiation consisting of electrons.
bremsstrahlung	Secondary photon radiation produced by deceleration of charged particles passing through matter.
collimator	A device designed to define beam shape, size, and direction.
cutie pie	A hand-held ionization chamber instrument having the approximate configuration of a very fat-barrelled pistol.
dead time correction	A correction applied to counter data for which the pulses are separated by times less than the system's resolving time. Also called coincidence loss correction in x-ray systems.
dose equivalent	The product of the absorbed dose, the quality factor, and other modifying factors needed in order to obtain an evaluation of the effects of ionizing radiation received by exposed persons. The unit is the rem.
exposure	The quotient of the total charge of electrons or positive ions produced (when all electrons liberated by photons interacting with a small volume of air are completely stopped) and the mass of that small volume.
extrapolation chamber	An ionization chamber having variable electrode separation, so that response may be measured at decreasing separations and extrapolated to zero chamber volume.

fluence rate	The fluence per unit time.
fluence	The amount of ionizing radiation (e.g., neutrons) which impinges upon a unit area.
flux	Fluence per unit time, for neutrons.
free-air chamber	A chamber in equilibrium with ambient air and having an electric field normal to the direction of a photon beam entering the chamber. The number of ion pairs produced by the photon beam is measured.
free-in-air	The condition (of an exposed RADIAC device) of experiencing minimal scatter and back-scatter of incident radiation by supporting devices, etc.
gamma radiation	Radiation consisting of photons, generally more energetic than x-rays.
geotropism	Dependence of an instrument's response upon its orientation with respect to the earth's gravitational field.
gray (Gy)	The SI unit of absorbed dose. For gammas, numerically equal to 100 rad or 1 Jkg^{-1}.
half-value layer	The thickness of a defined substance required to attentuate beam strength of a defined radiation beam by a factor of one-half.
ionization chamber	A gas-filled chamber which collects radiation-produced ion pairs of electrodes.
linear energy transfer (LET)	The linear rate of loss of locally absorbed energy by ionizing particles moving in matter. Usually expressed in units keV/μm.
metrology	The science of measurement.
moderator	Material introduced into a neutron beam in order to produce thermal neutrons.
phantom	An object having a configuration and composition which will scatter and backscatter incident radiation in a way simulating scatter by the human body.

proportional counter	A gas-filled detector tube operated in a voltage range such that the charge collected per isolated count is proportional to the charge liberated by the original event.
quality factor	A factor relating, or adjusting for, the biological damage done to tissue by different types of radiation, and depending on the linear energy transfer (LET).
radionuclide	A radioactive nucleus with a specific distinguishing composition of neutrons and protons and specific energy state(s).
rem	Roentgen equivalent, man, the unit of dose equivalent. Being replaced by the sievert, 1 rem = 0.01 Sv.
roentgen (R)	That unit of exposure (quantity of ionizing radiation) that will produce one electrostatic unit (ESU) of positive and negative charges in one cubic centimeter of air at standard temperature and pressure (STP).
room scatter (room return)	Radiation scattered into detectors from large area surfaces such as walls and floors. Also called wall scatter.
slab source	A flat radiation source having dimensions which are much larger than the source-to-target distance.
standard photoneutron source	A source consisting of radium encased in a thin-walled platinum-iridium or monel can, at the center of a sphere of beryllium. The latter is enclosed in a thin jacket of aluminum.
standard temperature & pressure (STP)	e.g., 22°C and one atmosphere pressure (760 mm Hg).
TEMPEST	A standard for limiting compromising emanations (unintentional intelligence-bearing signals which could reveal sensitive information).
thermalization	Production of thermal neutrons by passage of higher energy neutrons through matter containing a high percentage of hydrogen atoms (e.g., polyethylene).

thermal neutrons	Neutrons whose energy corresponds approximately to the mean thermal energy of matter at the ambient temperature.
tolerance certification	A procedure employed in calibration laboratories which handle large numbers of inexpensive but reusable dosimeters. A value of the desired accuracy or tolerance range is chosen. Dosimeters reading outside of that range are discarded and the remainder are certified as calibrated.
μ_{en}/p	Mass-energy absorption coefficient for tissue.
W/e	Average energy required to produce an ion-pair in air.

ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
AFRRI	Armed Forces Radiobiology Research Institute
Am	americium
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BCD/BCS	British Calibration Service
BCIF	Blacktail Canyon Irradiation Facility
Be	beryllium
BIPM	Bureau International des Poids et Mesures
BPNW	Battelle Pacific Northwest Laboratory
CECOM	Communications Electronics Command
cGy	centigray = 0.01 gray
Ci	curie
Co	cobalt
CRCPD	Conference of Radiation Control Program Directors
Cs	cesium
DIN	Deutsche Industrie Norm
DOE	US Department of Energy
EM	electromagnetic
EMI	electromagnetic interference
ESU	electrostatic unit
eV	electron volt
FEMA	Federal Emergency Management Agency
Gy	gray

HC	homogeniety coefficient
HPS	Health Physics Society
HVL	half-value layer
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Standards Organization
keV	kiloelectron volts
krad	kilorad
kV	kilovolt
kVcp	constant potential kilovolts
kVp	kilovolts peak
LET	linear energy transfer
mA	milliampere
MeV	megaelectron volts
MIL-SPEC	Military Specification
MIL-STD	Military Standard
MOS	Military Occupational Specialty
MQA	Measurement Quality Assurance
mrad	millirad
NBS	National Bureau of Standards (now NIST)
NCRP	National Council on Radiation Protection
NIST	National Institute of Standards and Technology (formerly NBS)
NRC	Nuclear Regulatory Commission (also NUREG)
NRPB	National Radiation Protection Board
NUREG	Nuclear Regulatory Commission (also NRC)
NVLAP	National Voluntary Laboratory Accreditation Program
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
PC	personal computer
PTB	Physikalish-Technische Bundesanstalt
Pu	plutonium
R	roentgen
Ra	radium
rad	radiation absorbed dose, 1 rad = 0.01 Gy
RADIAC	Radiation Detection, Identification, and Computation
RF	radio frequency

SI unit	from Système International d'Unités
STP	standard temperature and pressure
Sv	sievert, cf. rem
TECOM	Test and Evaluation Command
TLD	thermoluminescent dosimeter
TMS	Technical Management Services, Inc.
TOP	Test Operating Procedure
μGy	micro gray
USAEPG	US Army Electronic Proving Ground

APPENDIX F. DISTRIBUTION LIST

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